Technology for the United States Navy and Marine Corps, 2000-2035

Becoming a 21st-Century Force

VOLUME 5 Weapons

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"Technology for the U.S. Navy and Marine Corps
2000 - 2035 Becoming a 21st Century Force"

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Technology for the United States Navy and Marine Corps, 2000-2035

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VOLUME 5 Weapons

Panel on Weapons
Committee on Technology for Future Naval Forces
Naval Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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Preface

This report is part of the nine-volume series entitled *Technology for the United States Navy and Marine Corps: Becoming a 21st-Century Force*. The series is the product of an 18-month study requested by the Chief of Naval Operations. To carry out this study, eight technical panels were organized under the Committee on Technology for Future Naval Forces to examine all of the specific technical areas called out in the terms of reference.

On November 28, 1995, the Chief of Naval Operations (CNO) requested that the National Research Council initiate, through its Naval Studies Board, a thorough examination of the impact of advancing technology on the form and capability of the naval forces to the year 2035. The terms of reference of the study specifically asked for an identification of "present and emerging technologies that relate to the full breadth of Navy and Marine Corps mission capabilities," with specific attention to "(1) information warfare, electronic warfare, and the use of surveillance assets; (2) mine warfare and submarine warfare; (3) Navy and Marine Corps weaponry in the context of effectiveness on target; [and] (4) issues in caring for and maximizing effectiveness of Navy and Marine Corps human resources." Ten specific technical areas were identified to which attention should be broadly directed. The CNO's letter of request with the full terms of reference is given in Appendix A of this report.

The Panel on Weapons was assigned the responsibility of considering the evolution of naval weapons over the next 25 to 35 years. As part of its effort particular attention was directed to item 4: "Technologies that may advance cruise and tactical ballistic missile defense and offensive capabilities beyond current system approaches should be examined. Counters to conventional, bacteriological, chemical and nuclear

warheads should receive special attention." Attention also was directed to item 5: "The full range of Navy and Marine Corps weaponry should be reviewed in the light of new technologies to generate new and improved capabilities (for example, improved targeting and target recognition)."

Panel membership included broad expertise in research and development associated with weapons systems and expertise in acquiring, fielding, and using such systems. Areas of expertise included naval guns, torpedo systems, chemical and biological defenses, arms control issues, mines, explosives, warhead development, sensors, guidance, surveillance, lasers, ballistic missile defense, directed-energy weapons, pulsed-power systems, undersea systems, nuclear weapons, and data-link requirements.

To carry out its task, the panel met 10 times to receive briefings from Service and industry representatives, visit facilities, deliberate, and draft its report. In addition, the panel participated in the three plenary meetings for the overall study. The first, in March 1996, was addressed by the Chief of Naval Operations and many high-level officials of the Navy Department, the other Services, the Department of Defense (DOD), and industry. This organizational meeting conveyed a common, starting information base to the entire study membership. At the second plenary session, in October 1996, all the members of the study had their first opportunity to review each other's work, to see how the results of all the panels' work were coming together into an integrated message, and to feed the results back into their own efforts. The third plenary session, in March 1997, served as a coordination and writing session in which all of the panels' reports and the overview report were completed for final review. The panel chair and vice chair also participated in bimonthly meetings of the Committee on Technology for Future Naval Forces. These meetings served to inform the panel chairs and study leadership of progress in the individual panels' efforts and to resolve issues that cut across the responsibilities of more than one panel. The meetings also helped to ensure that common attention was paid to the interrelationships among the diverse panel outputs and the significance of those outputs for the naval forces.

The panel found its charge to be somewhat daunting in that weapons cannot be considered in isolation. Projections about the future weapon set of naval forces are dependent on assumptions concerning many intrinsically unknowable factors such as the evolution of relevant technology, the projected capabilities of future weapon transport and launch platforms, weapon costs, defense budgets, weapon choices by other Services, expectations with regard to future threats, military doctrine, and presumptions related to the modes, types, and national objectives of future conflicts.

The panel could not pretend to be expert in all of these areas and was forced to make estimates that may or may not prove to be an accurate representation of future reality. Although the panel views these as reasonable estimates, they should not be interpreted as precise forecasts of the future.

At the onset of this study, the panel wrestled with the question of what a weapon is. In the past, weapons were generally understood to be devices that were delivered by naval forces to persuade or deter current or potential adversaries from continued resistance and further pursuit of actions that the United States found to be inimicable to its national interests. Modern weapons are only one component of a complex system that involves sensors, data links, target selection, fuse technology, techniques for the negation of enemy countermeasures, and the release of either explosive or electromagnetic energy in a form that will limit an adversary's further ability to continue a conflict.

This extended definition of weapons caused the panel to consider the possible future evolution of areas of technology such as sensors, guidance, communications, target selection, and nontraditional approaches to naval conflict. Although these considerations caused a degree of overlap with the work of some of the other panels, liaison was maintained to ensure consistency of approach and results.

The panel encountered other limitations in its efforts. Naval weapons vary from nuclear weapons to less-than-lethal weapons. The panel devoted significant time and effort to the problems associated with nuclear weapons, particularly those associated with the Navy's current inventory of aging strategic missiles, and the utility of earth-penetrating weapons with nuclear warheads designed to attack repositories of deeply buried weapons of mass destruction. Ultimately, however, the panel elected not to make any recommendations with regard to these problems because any weapon decision in these areas must of necessity be a national decision based on national policy with respect to the further development and conditions of use of such weapons. In this area many serious long-term issues exist that call for an extended national debate whose outcome will have a profound impact on future national policy and on the future composition, structure, and missions of the naval forces.

At the other extreme are many techniques, such as offensive information warfare and less-than-lethal weapons, that proved to be relatively difficult for the panel to consider. The panel was limited not only by the fact that detailed descriptions of effective techniques are generally classified, but also by the fact that the technology, the concepts of ownership of cyberspace, and the applicable laws and international treaties are all evolving rapidly. The panel believes that conclusions and recommendations formed today with regard to possible naval approaches to information warfare and other less-than-lethal techniques may have little relevance for naval forces of the year 2035. Nevertheless, the panel recognizes the extreme importance of nonconventional weapons and techniques in future naval operations, and it suggests directions and impacts that currently evolving technology may have on future conflicts.

A large fraction of all naval weapons are defensive in nature in the sense that they are designed to protect U.S. platforms and deployed ground forces from the effects of enemy weapons. Here again, weapons are only a relatively modest part

of the overall problem of developing a competent defense. Issues such as the reduction of the signatures of our own platforms, the performance of our own sensors, and the negation of an adversary's guidance and targeting capabilities are all components of the problem of developing more robust defensive systems. Since many of these areas were within the assigned purviews of other panels of this study, careful liaison was maintained to ensure consistency of results and conclusions.

Acknowledgments

In order to undertake this study, the Panel on Weapons needed to hear and review many presentations from representatives of the Navy, the Marine Corps, other Services and DOD agencies, national laboratories, federal contract research centers, academia, and industry. The complexity of arranging for these briefings was formidable. The panel is deeply grateful to Mr. James G. Wilson for his skill and patience in arranging for and scheduling these briefs. Without his efforts the panel's work would have been limited and incomplete.

The panel gratefully acknowledges contributions on explosives science and technology from Mr. Les Roslund and Mr. Robert Kavetsky of the Naval Surface Warfare Center, Indian Head Division (NSWC/IHD). Mr. Frank Tse (NSWC/IHD); Mr. Thomas Boggs and staff at the Naval Air Warfare Center (NAWC), including Ms. Alice Atwood, Mr. Stuart Blashill, Dr. Craig Porter, Mr. Scott Fuller, and Mr. John Robbins; and Mr. Robert Kavetsky (NSWC/IHD) and Mr. Stephen E. Mitchell (NSWC/IHD) contributed to the panel's thinking on propulsion science and technology. Dr. Klaus Schadow (NAWC) was helpful with contributions on air-breathing missile propulsion.

The panel also owes a debt of gratitude to members of the staff of the Naval Studies Board, particularly Ms. Mary G. (Dixie) Gordon, Ms. Susan Campbell, and Mr. Christopher A. Hanna, for their hard work, support, and unfailing good spirits during meetings and in the preparation of the final report.

The panel also wishes to acknowledge the many valuable comments and discussions it had with Mr. David Heebner, chair of the Naval Studies Board; Mr. Seymour Deitchman, study coordinator and integrator; the chairs of the other panels; and members of the study's Advisory Council.

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Executive Summary

CONTEXT

Political, technological, military, and economic trends will affect the way naval forces are structured in the future and the weapons with which they will be equipped. The Panel on Weapons foresees that during the next 25 to 35 years, naval forces will be called on to provide part of the U.S. response to a variety of situations that vary from major regional conflicts (MRCs) to operations other than war (OOTW) that may involve anything from disaster relief to hostage recovery. Naval forces should be equipped with appropriate, effective, and affordable weapons to respond to the expected range of conflicts in which they may be involved.

The panel is mindful that there is a worldwide trend among potential adversaries in the proliferation of increasingly capable air defenses, antiship weapons, sea and land mines, better surveillance capabilities based on commercial and some national satellite systems, quiet submarines, modern land combat systems, and possibly chemical, biological, or nuclear weapons (conventionally grouped under the rubric of weapons of mass destruction [WMD]) with medium-range weapon-delivery capability. In the face of these potentially increased military capabilities of future adversaries, there remains a need for Navy and Marine Corps forces to be equipped to destroy large numbers of fixed targets, and an even larger number of mobile or relocatable targets, while maintaining an antisubmarine warfare (ASW) capability and an antinuclear posture in case a peer competitor resurfaces.

The strategy of naval forces to project power is often based on the insertion of Marine Corps early-entry combat forces. Threat environments will force

insertion from a greater standoff distance from shore than before (to increase the survivability of the amphibious forces). Marine combat forces will have the option to select areas tactically preferred but previously not reachable and be supported with sea-based area surveillance and firepower. This is expected to reduce the logistic support the marines would have to take ashore with them and would permit deploying smaller forces to more strategic points to control a larger area in the initial phase of an operation. In its study of weapon mix to achieve these objectives, the panel took into account differences in requirements prior to landing troops from those required to support and sustain them afterward.

FIRE SUPPORT FROM THE SEA

The Marine Corps concept of future operations will require weapons from the sea capable of delivering the following munitions:

- Area munitions against soft targets such as troops, trucks, or depots;
- Precision munitions with unitary warheads against hardened fixed or stationary targets; and
- Smart submunitions for use against mobile targets and targets with relatively unique signatures.

Except for targets that can be engaged by gunfire (inaccurate and short range) or cruise missiles (limited in numbers, and expensive), the Navy's current capability to destroy these targets rests entirely with carrier-based aircraft. The panel believes that aircraft cost and vulnerability (except at sanctuary altitudes and standoff distances) will require that the Navy have alternative shipboard weapon systems to share the task of fire support from the sea. The long time of flight and high cost of the Tomahawk land attack missile (TLAM) also require that faster and cheaper long-range surface-to-surface weapons be developed.

Future alternatives include an arsenal ship, or perhaps an arsenal submarine, equipped with a deep magazine of long-range precision-guided rockets and the development of longer-range projectiles for naval guns. The panel concluded that there is no practical way that existing naval guns could be upgraded with new munitions to provide ordnance delivery to ranges between 200 and 600 km with the required warhead payloads. Thus, the panel concluded that fire support from the sea should be provided predominantly by precision-guided solid rocket-propelled long-range ballistic missiles. These missiles could be built with various calibers and equipped with a variety of warheads/payloads and terminal-guidance systems, all launched from vertical launch systems (VLSs).

As an interim measure until such weapons are developed, the panel concluded that the extended-range guided munition (ERGM) should be developed and the Navy's present 5-in./54 guns should be upgraded to 5-in./62 to increase the reach of shipboard guns to about 60 nautical miles.

ANTISHIP MISSILE DEFENSE

Many nations are acquiring highly maneuverable, stealthy, subsonic, and/or supersonic antiship missiles. Many will be sea skimmers that reduce to a minimum the reaction time available to the defense. The panel concluded that with the use of networked surveillance and sensor capabilities and airborne antiair assets, and with the use of high-acceleration and agile surface-to-air missiles (SAMs), the Navy will be able to cope with at least modest antiship missile attacks expected from potential adversaries. However, to gain the maximum effectiveness from all available weapons, the Navy must pursue programs that provide for the required detection and tracking capabilities through the use of networked sensor systems and improved SAMs and air-to-air missiles (AAMs) all capable of dealing with advanced threat cruise missiles.

DEFENSE AGAINST THEATER BALLISTIC MISSILES

Many potential adversaries will possess theater ballistic missiles (TBMs) armed with conventional weapons and WMD, i.e., chemical, biological, and nuclear warheads. Without a competent defense, many forms of naval force power projection, such as amphibious operations, may incur unacceptable losses. The panel concurs with the Navy's plan for the initial development of a terminal defense against short-range TBMs with unitary warheads and later growth to a more robust hit-to-kill pre-apogee intercept system, if necessary, to counter long-range TBMs. Such a long-range system could become increasingly important to such missions as theaterwide air defense. The Department of the Navy has no plans to defend against TBMs that may be designed to deploy their submunitions shortly after booster burnout. This threat could prove to be a "showstopper" for Navy and Marine Corps landing operations, and the panel believes that the Department of the Navy should undertake a serious exploration of options for a naval boost-phase intercept capability.

AIR-TO-SURFACE WEAPONS

The panel envisions that 25 to 35 years in the future, a greater percentage of air-to-surface ordnance delivery will be accomplished with standoff air-to-surface weapons. Although these weapons ultimately must be capable of receiving target information from off-board sensors, they also must have autonomous capabilities to continue their attack even in the face of countermeasures leading to target sensor information dropouts. In this respect, coupling an inertial navigator with the terminal guidance system has considerable merit. The panel noted that it is important that, for weapons employing seekers for target acquisition, the type of weapon sensor used should operate on the same physical phenomena as the acquisition and surveillance sensors, since a target detected by one type of sensor may not be detectable by

another. It recognizes that if a surveillance sensor sees the target, there is a good chance that the weapon's acquisition sensor will see it also. However, the panel is concerned with the fact that if the available weapons on a given sortie have acquisition sensors that are different from the surveillance sensor (assuming only one sensor per weapon), the weapon may or may not acquire the target. All things considered, the panel believes that in most cases it will be desirable to have a common sensor. This will be particularly true in situations where the surveillance sensor is a ground observer that guides the weapon to the target with a correlation guidance system. For example, if a target is detected by foliage-penetrating radar, a weapon with an infrared (IR) seeker will not be able to engage. Moreover, if the operation of the weapon's fuse is based on radar, it may not function reliably in dense foliage. The trend toward long-range standoff air-to-surface weapons also has implications regarding the types of naval aircraft that will be needed in the future. The aircraft that deliver such weapons do not have to be high-performance aircraft; they must, however, carry large numbers of missiles, but still are restricted by the total payload weight of carrier-based aircraft. Future munitions should be highly common with surface-to-surface systems.

One type of air-to-surface weapon that the panel believes is critical to future operations is a standoff missile similar to the high-speed antiradiation missile (HARM) designed to suppress enemy air defenses. Precision targeting may reduce the need for an antiradiation homer; however, the panel believes that the utility of such a weapon is high and that its capabilities should be extended beyond those of the current HARM system. One reason for the continued retention of HARM-like weapons in the future weapon inventory is that external sensors that are used to geo-locate a radar from standoff distances generally do not provide a small enough error ellipse to allow the target to be attacked by a weapon that is vectored to a Global Positioning System (GPS) coordinate. Thus, unless there is an improvement in the location accuracy of future nonimaging standoff sensors, a residual HARM capability will be necessary.

AIR-TO-AIR WEAPONS

The panel concluded that the emerging concept of networked integrated sensors providing fire-control quality information to all potential antiair weapon launch platforms—aircraft and others—represents a fundamental shift with broad implications for air-to-air weapons. The panel concluded that the future emphasis should be on long-range interceptor missiles enabled by networked target-acquisition sensors and advanced target-identification capabilities. Air-to-air weapons should also evolve to include greater counterstealth capability, particularly to counter low-observable (LO) cruise-missile threats, and should include multimode seekers capable of longer-range semiautonomous engagements. One nonmissile option offering real potential is the concept of an active close-in self-protection capability based on solid-state laser technology. One important impli-

cation of the panel's conclusions is that highly agile aircraft will be less desirable in the future as compared with aircraft capable of carrying relatively large inventories of standoff strike and air-to-air weapons. If supplemented with long-range ship-to-air missiles that the aircraft might forward pass, for example, the air-dominance capability would be enhanced even more.

NUCLEAR WEAPONS AND OTHER APPROACHES TO THE NEGATION OF HARD-TO-DEFEAT TARGETS

Based on current national policy, the Navy may expect to be directed to maintain a strategic nuclear weapons deterrent capability against the reappearance of a major global nuclear threat or other weapons of mass destruction. As the current stockpile ages, the Navy may be expected to be directed by national authority to replace existing weapons with either replicate weapons of new vintage or upgraded design depending on national policy. A low-yield (10 tons to 1 kiloton) nuclear warhead on a precisely delivered penetrating weapon may have an important and growing role because of the need to attack and destroy very hard and deeply buried targets that cannot be destroyed by even large conventional warheads. A logical hierarchy of approaches to destroying hard buried targets and minimizing the collateral damage would begin by considering attacking just the umbilicals of the target (power, communications, and air treatment). Next are the possibilities for the use of high-velocity kinetic-energy penetrators or penetrators containing explosive directional warheads. The possible use of multiple penetrating weapons with zero circular error of probability (CEP) that enter the target area at the same point and from the same direction in order to gradually dig out a deep facility should be considered. If none of the above approaches is a robust solution, national authorities should give due consideration to the deployment of low-yield nuclear warheads on precision, high-velocity, penetrating missiles. An adversary can elect to make the problem of destroying buried targets even more difficult by emplacing them under schools, hospitals, or heavily populated areas. In effect, an adversary might use his own population as a form of cover and protection for valid military targets.

MITIGATING THE IMPACT OF WEAPONS OF MASS DESTRUCTION

The panel recognizes that the use, or threat of use, of chemical, biological, or nuclear weapons on land and at sea can profoundly affect the ability of the United States to project its forces. The panel also realizes the many ways that WMD can be delivered: by TBM, cruise missile (CM), aircraft, and ships against sea targets and also by trucks, artillery, and special operations forces (SOF) against land-based targets. Defending against such diverse threats will require a variety of defensive measures that must be integrated if an effective defense is to be at-

tained. There is uncertainty as to whether naval forces will be able to operate continually in a chemical and/or biological weapon effects environment, and there is thus a need for an overall naval chemical and biological warfare (CBW) doctrine. The use of active measures to deny WMD use is discussed elsewhere in this document, but emphasis should be given to the development of rapid and remote CBW detection to allow adequate time to implement appropriate passive defensive measures, as well as attack warning available from other radar and IR sensors. The importance of improved passive defenses against biological and chemical attack must also be recognized and supported programmatically.

ANTISUBMARINE WARFARE WEAPONS

Submarines in the hands of even less capable adversaries will remain a formidable threat to the conduct of naval (Navy and Marine Corps) operations near shore. Operations in shallow water near hostile shores make it difficult to conduct the multilayered (submarine barriers, patrol aircraft, and surface ship point defense) antisubmarine warfare (ASW) defense that was designed against the past Soviet threat. The Navy now has an inadequate capability to defend against a near-shore modern electric-drive submarine. Therefore, the ASW defense capabilities of naval forces must be improved. The panel believes that an aggressive antitorpedo defense must be a mainstay of such a capability.

Offensive weapons against hostile submarines have not received much attention in recent years since the previous Soviet ASW threat diminished. In the meantime, however, improvements in hostile submarine capabilities have continued. The panel believes that improvements on present submarine weapons can provide an adequate capability against the generally smaller submarines in the hands of potential adversaries.

OFFENSIVE MINE WARFARE

U.S. offensive mining capabilities (against hostile submarines) are represented by the encapsulated torpedo (CAPTOR) mine. The panel concluded that a networked underwater sensor field (interconnected by acoustic communications), when coupled with an autonomous unmanned vehicle (AUV) that can attack any target in the sensor field, may be a cost-effective approach for offensive mines to sanitize a fairly large volume of water. In such a system the less expensive sensors would be proliferated, whereas only a few expensive weapons would be needed to cover a given volume of water.

OTHER NAVAL WEAPONS AND TECHNIQUES

Although there is an enduring need for weapons to destroy targets, there is also an emerging need to develop weapons that incapacitate the enemy and re-

duce his will to fight. During Desert Storm, some of these effects were achieved by conventional weapons that destroyed the will of the enemy army to fight, the enemy's electric power generation and distribution systems, and command-and-control capabilities. The panel sees an expanded need for weapons and concepts specifically designed for incapacitating the enemy's infrastructure and the enemy's will and ability to fight while causing minimal civilian fatalities or serious collateral damage.

Another important area for the Department of the Navy to pursue is the ability of the naval forces to conduct information warfare (IW), particularly at the outset of hostilities to confuse and deny an enemy's ability to command and control its forces. The successful implementation of IW could be seen as a force multiplier for the United States.

THE ECONOMICS AND SPEED OF TARGET DESTRUCTION

The panel compared the cost and time required to wage a successful campaign against some conceptual adversaries and concluded that even when taking into account the relatively high cost of smart weapons, the predominant use of smart weapons, launched from relatively safe standoff ranges, will minimize the cost and duration of a campaign and will minimize U.S. casualties and the expenditure of military assets.

The panel concluded that properly designed precision-guided rockets offer the advantages of supersonic speed and can provide the weapon ranges required along with a more benign launch environment for guidance electronics. In addition, they can easily be scaled to a variety of sizes. The panel notes that such weapons can have a steep learning curve (large cost reductions with increasing quantities) and commonality of components.

In such weapons, the cost of the guidance subsystem generally dominates the weapon cost. Typically, guidance electronics may be half of the total cost of the weapon. For this reason, the reduction of the cost of guidance electronics is of utmost importance. IR and video seekers, one-way (command) data links, GPS, and new, low-cost Inertial Measurement Unit (IMU) weapon navigation systems tend to be low-cost components. Two-way, high-data-rate data links and long-range radar seekers are examples of high-cost components of a guidance system. System designs that utilize lower-cost components, standardized across weapons using similar components to achieve higher production volumes and (thus) lower cost, are approaches to the reduction of guidance-system cost and hence total weapon cost. The panel concluded that significant reductions in the unit cost of weapons can be achieved by a careful exercise of these principles, thus making the use of a higher percentage of smart weapons in future conflicts more affordable.

GENERAL CONCLUSIONS

A more exhaustive and detailed list of the panel's findings, conclusions, and recommendations is provided in Chapter 10 of this report. In general, the panel concluded the following:

- Significant changes in Navy and Marine Corps strategy and weapon mix are needed for the conflicts foreseen for the next 25 to 35 years.
- Increased use of smart weapons can significantly reduce the total cost and logistic requirements of a conflict, while reducing its duration. They can also reduce the vulnerability of launch platforms and munition caches as well as place less stress on dockage.
- If not addressed successfully, surface-ship survivability in the face of enemy TBMs, WMD, cruise missiles, submarines, and mines could be a showstopper in future power-projection operations.
- Aircraft attrition should be minimized by the greatest possible use of standoff weapons in both air-to-air and air-to-surface combat in addition to other factors such as stealth, electronic warfare (EW), and tactics. In general the greater the standoff range, the more costly the weapon. Weapons and weapon delivery system concepts may vary from relatively short-range accurate weapons such as the joint direct-attack munition (JDAM), delivered by stealth aircraft, to precision weapons launched by sea-based platforms from significantly great standoff distances. The optimum system design will be a complex function of assumed aircraft costs and attrition rates, the support costs of sea-based aircraft versus arsenal ships, the total number of targets to be destroyed, target detection and designation problems, the cost of weapons as a function of standoff range, and the number of weapons that must be delivered per unit time.
- If aircraft attrition can be eliminated by the use of true stealth aircraft, then short-range, precision-guided, air-to-ground munitions of the JDAM class represent the best means of minimizing ordnance costs in an extended air campaign with many ground targets.
- If there is no prospect that stealth aircraft will be available in adequate numbers, then aircraft attrition is best minimized or avoided by either the extensive use of long-range air-to-surface missiles or the extensive use of sea-launched precision-guided rockets.
- Rocket-powered, precision-guided, long-range (ballistic) weapons launched from surface ships or submarines that are equipped with a variety of warheads and some with terminal guidance could significantly augment the early naval response to an adversary's military actions and satisfy the offshore firepower support requirements of engaged forces ashore.

PRIMARY RECOMMENDATIONS—INITIATIVES FOR WEAPONS AND SPECIAL TECHNIQUES

The panel recommends the following new Department of the Navy initiatives:

- *Surface-to-surface (also applicable to subsurface-to-surface and air-to-surface):* a family of low-cost, high-volume, long-range precision ballistic weapons; and
- *Air-to-air:* a new weapon to support a long-range engagement capability that exploits airborne cooperative engagement capabilities (CECs).

The panel also recommends continued Department of the Navy emphasis on the following:

- *Air-to-surface:* continue the trend toward smart precision standoff and direct-attack munitions.
- *Cruise missile defense/antiballistic missile (CMD/ABM):* continue the pursuit of an integrated, all-platform, multilayer defense with a variety of weapons.
- *Undersea warfare:* weapons optimized for offensive and defensive operations in littoral regions.
- *Offensive/defensive mine warfare:* mines operated by networked sensor systems.
- *Special techniques:* emphasize special lethal and less-than-lethal warfare techniques as well as an integrated WMD defense.

1

Introduction and Overview

In any given conflict 25 to 35 years in the future, the Navy and Marine Corps weapons of choice and the means of propelling and guiding them to their intended targets will be driven by factors such as the following:

- The capabilities of available operational systems and platforms;
- The contemporary technology for identifying and tracking the location of the target (including cueing, localization, and identification);
- The availability of robust navigation and communication systems for control and guidance of the weapons;
- The midterm evolution of fundamental technology, such as microelectromechanical systems (MEMS), digital processors, propellants, and materials; and
- Overall weapon costs related to propulsion, launch system, guidance, control, and yield.

The panel believes that in the future, some weapon systems, such as those used for support of land forces and those used for attacks designed to deter or punish an adversary, probably will contain only evolutionary modifications of current weapons. Other weapons, such as, for example, a hypothetical cruise missile that carries a repetitive electromagnetic pulse (EMP) generator and is designed to attack and disable electronic devices, or a hypervelocity missile, might be entirely new both in concept and technology.

Except for weapons and weapon systems related to incapacitating (less than lethal) techniques, offensive information warfare (IW) techniques, infrastructure attack, and potential variants of mine warfare, the concepts and hypervelocity

missiles for employment all of other classes of weapons listed here are reasonably mature, and the issues related to their design and employment have been debated extensively over the last 40 to 50 years.

Weapons must be considered in the context of the class of target they are designed to attack, existing limitations on acceptable levels of collateral damage, and the target-selection and designation system with which they are designed to operate. It is anticipated that 25 to 35 years in the future, the target set the naval forces will be called on to attack will include the present list of tactical and strategic targets (e.g., WMD; critical command, control, communications, computing, and intelligence [C^4I] nodes; transportation hubs; airfields; logistics centers; both organized and guerrilla military forces) and attacks on targets that are components of an adversary's civil and governmental infrastructure (public utilities, telecommunications networks, banking systems, mass media, law enforcement databases, civil transport, and so on).

OFFENSIVE WEAPONS—BASIC CONSIDERATIONS

As the panel examined the issue of how expected changes in technology will affect naval warfare in the future, it was led to ask three questions:

1. Which specific elements of evolving technology will make a significant difference in the way future naval forces operate and are configured?
2. What are the major changes foreseen in weapons that will be available to future naval forces?
3. What are the implications of the changes implied by the application of foreseen technology for the constitution of future naval forces and for the ways in which these future forces might be employed?

The panel's approach to each of these three questions is outlined and then discussed in some detail in the sections that follow.

Changes in Technology That Will Make a Difference

The panel believes that the three most important results of the application of existing or currently foreseen technology will be the enhanced availability of information, the broad availability of precision weapons, and the general availability of distributed firepower.

- Enhanced availability of information
  - —Adequate connectivity and targeting data available at every weapon launch platform
  - —Networked sensors and cooperative engagement capability for all air-to-air, ship-to-air, and undersea engagements

- Precision weapons
  - — Geodetic guidance based on low-cost miniaturized GPS/IMU technology
  - — Imaging sensors and image transfer correlation sensors
  - — Low-cost data links
- Distributed firepower
  - — Standard VLS cells
  - — Standardized families of ballistic missiles
  - — Missionized mix and match weapon loadouts.

Enhanced Availability of Information

Enhancements in the availability of information will be a consequence of the probable universal existence of broadband connectivity, which will allow each weapon launch platform to be provided with the timely and accurate targeting data that will be needed to support the use of precision weapons. In addition to greatly enhanced connectivity, the available targeting data will be more effective and precise because of the future use of networked sensors that will provide more continuous and complete tracks of moving targets than can be provided by a single sensor.

Precision Weapons

Because of their reliability and high probability of hitting and damaging or destroying their intended targets, precision weapons will be widely used by naval forces. Indeed, if the current combat paradigm, which places heavy demands on logistics, is to be improved upon in any significant way, it will be necessary for precision weapons to be employed extensively by all of the Services. Currently, precision weapons are expensive and their use is restricted to high-value targets; in the future, it will be necessary to extend their use to a much broader target set, including those of low and medium value. Large numbers of weapons will be needed, and major reductions in unit cost are required if this new vision of combat is to be realized. The panel looks to two factors to bring about such cost reduction:

- *Technology advances in sensors, processing, control, and communication systems:* advances directed toward small size and low cost as well as toward the traditional goal of improved performance. Much of this advance will be derived from the adaptive employment of commercial technology. In addition, DOD-funded research and development (R&D) must continue and expand its emphasis on design to cost and on low-cost manufacturing technology.
- *Scale of manufacturing:* the need for large numbers of weapons and correspondingly large production runs will in itself reduce the unit cost. The mandated use of interchangeable common modules wherever feasible can result in additional cost reductions.

Distributed Firepower

The panel also believes that the current trend to distributed firepower will increase. Standard vertical launch system (VLS) cells will be available on most major combatants. Future VLS cells will incorporate a flexible design that will allow each cell to accommodate as desirable or necessary weapons of multiple diameters that are components of standard weapon families. The panel postulates that each VLS cell will have a customized loadout that has been mixed and matched to its current specific mission assignment. One major shortcoming of the dependence on VLS weapons is that the magazine is finite. If a VLS ship cannot be reloaded at sea, it must return to port when its magazine has been exhausted. Current technology does not allow at-sea reloading of VLS tubes. The concept espoused in this paragraph implicitly assumes that the problem of reloading VLS ships at sea will be solved. The problem being addressed here is formidable and will not be resolved without a major R&D effort.

Major Changes Foreseen in Offensive Weapons

- Sea-launched precision-guided tactical ballistic missiles
  - Evolution of family of relatively inexpensive surface-to-surface missiles
  - Increased magazine depth and sustainability of surface forces
- Alternatives to sea-launched precision-guided tactical ballistic missiles
- Emphasis on medium- and long-range air-to-air and long-range ship-to-air missiles
- Target detection and track based on networked distributed sensors
- Increased role for incapacitating and other special-purpose weapons and techniques
  - Incapacitating weapons to disable personnel, ships, aircraft, and infrastructure
  - New weapons and techniques for offensive IW, infrastructure attack and disablement, conflict in urban areas, and mining
- New approach to mine countermeasures in very shallow water and the surf zone
- New missiles for nuclear warhead delivery—shorter ranges, zero CEP, small penetrating nuclear warheads

Sea-launched Precision-guided Tactical Ballistic Missiles

As discussed in the section entitled "Projected Evolution of Surface-to-surface Weapons" in Chapter 3 of this report, the panel projects the development of a family of relatively low-cost, sea-launched, solid-propellant, precision-guided tactical ballistic missiles, which will become the naval forces' dominant class of weapon for strikes at both fixed and moving targets. The panel envisages three

diameters of missiles (say, diameters of 5 inches, 10 inches, and 21 inches). The current VLS cell is normally configured to launch missiles that are a maximum of about 21 feet long and 21 inches in diameter. The panel believes that existing VLS cells could be modified so that they could be used to launch any of the three diameters of missiles.

Although it has not been implemented to date, the panel believes that it would be possible to modify the design of existing VLS cells to allow double stacking of 5-in. and 10-in. missiles in a VLS tube. If double-stacking designs were introduced, a single VLS cell might carry eight 10-in.-diameter missiles or as many as thirty-two 5-in.-diameter missiles. The availability of a double-stack option would greatly increase the magazine depth and sustainability of a fire-support ship. Under such circumstances, if an entire bay of 64 VLS cells were double stacked with 5-in.-diameter missiles, 2,048 missiles would be available.

The panel believes that a 5-in.-diameter ballistic missile might have a range up to 75 miles, and depending on warhead weight and staging design, a 10-in.-diameter missile might be capable of attacking some targets out to ranges of 150 to 200 miles. The largest rockets in this family will be configured with large payloads to attack surface targets out to the maximum ranges (600 km) permitted by treaty limitations.

One of the driving considerations in the choice of future weapons will be cost. The panel believes that the rocket family described in the text of this report can be produced at a cost that will be competitive with or cheaper than the cost of other weapons of comparable range, precision of delivery, warhead weight, and flexibility of use.

The panel recognizes that the unit acquisition cost of such high-performance missiles will continue to be relatively high. However, the panel believes that a complete calculation of the true cost of delivery of equivalent warheads at equivalent distances in the presence of a competent and unsuppressed air defense system by recoverable (but attritable) aircraft, whether inhabited or uninhabited, will drive the economics of such weapon delivery system reliance on ballistic missiles until air defenses are suppressed or eliminated. Except in extraordinary circumstances, nonstealthy recoverable manned aircraft will not be used for such missions.

The panel believes that the cost of precision-guided tactical ballistic missiles can be reduced significantly by the extensive use of interchangeable modular components. In order to realize an economy of scale, the same guidance systems, IMUs, and data links should be employed in every missile. Although it would violate the principles of optimum design for a multistage missile, the panel postulates that further economies of scale could be realized if all rocket motor stages of a given diameter rocket might be designed to be identical. The panel also believes that careful attention to specific design detail will also help reduce unit acquisition costs.

If the target location error (TLE) can be reduced to less than the guidance errors, extremely accurate guidance (1 to 3 meters) will permit many targets to be destroyed with somewhat smaller warheads than are used with current weapons. For fixed targets, accurate geodetic guidance will be achieved by the use of microminiaturized GPS receivers and extremely low drift rate miniaturized inertial navigation devices (IMU) that are based on the currently evolving technology for MEMS. Such high-performance IMUs will reduce vulnerability of guidance systems to GPS jamming. In addition, the relatively short time of flight of a ballistic missile provides a minimal amount of time for the effects of IMU drift to affect delivery accuracy.

The panel is cognizant of the limitations of weapon guidance accuracy. The foregoing discussion focuses on the key role that will be played in future weapons by miniaturized low-cost, low-drift-rate, highly accurate IMUs. The panel recognizes that in the near term, high performance and low cost may not be compatible goals. However, many organizations are aggressively pursuing the development of devices with these attributes. Although the reader cannot be assured that these efforts will be successful, the panel is optimistic that, given the level of effort involved, over the 35-year horizon of this study, the desired goals will be attained. Even perfect guidance will have little value in situations where the TLE is large. However, for situations where the TLE is small (< 3 m) and the target is not a distributed area target, extremely accurate guidance will permit many targets to be destroyed with smaller warheads than are used with current weapons. Again the panel recognizes that some extremely robust targets (e.g., bridge abutments and hard, underground targets) will require both extreme accuracy of placement and large warheads.

Weapon guidance to allow such missiles to acquire moving targets is an inherently more complex and time-critical process than the process needed to guide a weapon to a fixed location. Although much effort has been devoted to the development of automatic target recognition (ATR) systems so that future weapons can find their targets in a fully autonomous mode, success in these efforts has been limited. Based on progress to date, the panel suggests that it may be many years before all of the problems associated with ATR are completely resolved.

In the interim, before effective ATR is developed, many technologies are available for use in the guidance of a weapon to a moving target. As an example, if a data link is available between an observer who is simultaneously within line of sight of both the target and the weapon, an image of the target can be transferred to the weapon. If the weapon had an imaging sensor that replicated the sensor of the observer, then a correlation processor would allow the weapon to be guided to the target. Other guidance systems such as that employed in the brilliant antitank (BAT) weapon are operational and are fully capable of permitting a weapon to engage mobile targets. The panel is confident that evolving technologies (e.g., ATR, correlation sensors, various imaging, and multispectral and hyperspectral sensors) will reduce the problem of attacking mobile targets.

Alternatives to Sea-launched Precision-guided Tactical Ballistic Missiles

The panel has reviewed the projected evolution of alternative systems (gun-launched projectiles, cruise missiles, and air-to-surface weapons) for delivery of ordnance to a remote adversary. Weapons of these types will certainly remain in the operational inventory for many years into the future. Certainly the performance of these classes of weapons will be improved and will exceed the performance of equivalent weapons currently available to operating forces. However, based on the discussion presented in the text of this report, the panel believes that, over a period of time, the intrinsic advantages of sea-launched, precision-guided tactical ballistic missiles, and the intrinsic disadvantages of other forms of ordnance delivery in several scenarios, will gradually cause such missiles to become more acceptable as the preferred means of ordnance delivery over guns and aircraft.

Gun Variants

As discussed in the section entitled "Guns" in Chapter 3 of this report, the panel has examined a number of new concepts for guns including vertical gun systems (VGASs), coil guns, rail guns, electrothermal (ET) guns, electrothermal-chemical (ETC) guns, and various proposals for extending the ranges of existing naval guns with the use of the ERGM and with increased caliber gun barrels. The panel believes that the ERGM would certainly provide the naval forces with an important and much needed near-term capability that would increase the range of its 5-in./54 significantly. As the range of a 5-in. projectile is increased, the weight of the warhead impacting the target decreases. In effect, ERGM, which is an explosively launched small missile, achieves its range by the combined use of the kinetic energy imparted at launch and the stored chemical energy contained within the body of the projectile that is used for a sustainer motor. The design extremes go from a projectile that only uses kinetic energy imparted at launch (conventional naval shells) to a projectile that only uses internal stored chemical energy (rocket or cruise missile).

Cruise Missiles

Air-breathing cruise missiles should remain in the operational inventory for much of the next 25 to 35 years. The range of cruise missiles designed for use against static targets will be determined by their engine efficiency and mass fraction, by the energetics and the volume of the propulsive fuels they carry, and by aerodynamic design factors (i.e., lift-to-drag ratio and payload weight). Although more energetic fuels are possible, the panel believes that the introduction of such fuels into operational weapon systems will, for reasons of operational safety, environmental handling problems, and cost, proceed slowly. Growth in

the volume of fuel tankage of current missiles may be achieved by shrinking the size of the warhead or by increasing the length and diameter of cruise missiles. Although this latter approach requires no new technology, it would be difficult to implement because of the costs of replacing legacy missile launch systems.

In recent years, air-breathing cruise missiles have proven to be an extremely important and effective weapon for the U.S. Navy. Their great range, large warheads, and accurate guidance have allowed the Navy to execute surgical strikes against fixed targets with a relatively high probability of target destruction. They have the added advantage that, in the course of such strikes, no aircraft have been lost and no U.S. pilots have been captured and displayed on CNN.

The technology of the current Tomahawk land attack missile (TLAM) has been upgraded, and there is every evidence that it will continue to be upgraded. Major efforts have been made to increase the stealth of the TLAM and to reduce its vulnerability to enemy air defenses. Suggestions have been made for the installation of new and improved data links that will help with both bomb damage assessment (BDA) and alternate target assignment. New warhead payloads have been suggested for the TLAM. Among the concepts being considered is the use of the TLAM as a dispenser for the BAT submunition. The panel has not examined the feasibility of all of the many possible alternate warhead designs that have been suggested. What is clear is that the TLAM, depending on the fraction of its internal volume used for fuel (and consequently range), has the capacity to carry a large warhead when measured both in weight and volume.

Despite its many advantages the panel believes that eventually, for many if not most missions, the TLAM and the joint air-to-surface standoff missile (JASSM) currently in development and their future variants will be replaced by precision-guided tactical ballistic missiles. TLAMs are ultimately subsonic vehicles that may take an hour or more to reach their intended target. They owe their survivability, in the presence of enemy air defenses, to the application of stealth techniques and penetration aids and to the careful employment of low-altitude trajectories that limit the opportunities of defensive forces to engage. These techniques certainly assure a high degree of survival in most current or foreseen environments. Nevertheless, looking 25 to 35 years into the future, the panel is not persuaded that the prognosis for survival of a low-altitude subsonic cruise missile is robust. A distributed air-defense system consisting of large numbers of shoulder-fired missiles would be difficult to suppress and would take a significant toll in incoming cruise missiles.

Rocket-propelled weapons with high-altitude trajectories that travel at speeds of between Mach 3 and Mach 5 would be virtually immune to all but the most sophisticated air defenses which should be suppressible by antiradiation missiles. Since a 21-in.-diameter rocket might carry almost the same warhead weight and volume as is carried by a cruise missile, and because of its ability to attack targets rapidly at range and its enhanced immunity to enemy air defenses, the panel

believes that ultimately precision-guided tactical ballistic missiles will become the weapon of choice for most missions currently assigned to TLAMs. The Strategic Arms Reduction Treaty (START I) between the United States and the former Soviet Union bars the use of surface ship-launched ballistic missiles with ranges greater than 600 km. Although the treaty is of finite duration, treaty compliance on surface ship ballistic missile range must, of course, be assured.

Air-to-surface Weapons

Over the last 25 to 35 years as the sophistication, range, and effectiveness of enemy air defenses increased, two principal trends—suppression of enemy air defenses and the development of long-range precision strike weapons—became essential for air-to-surface ordnance-delivery systems. Remarkable progress has been made and is continuing to be made.

Unfortunately there are limits to the effectiveness of the techniques for the suppression of enemy air defenses. A distributed defense system based on the use of shoulder-fired missiles is, and will continue to be, difficult to suppress. Fortunately such systems can be negated because generally they cannot engage targets that are flying at altitudes above 15,000 to 20,000 feet. Unless a significant but unforeseen change occurs in the energetics of missile propulsion, a sanctuary altitude will probably continue to exist for any missile that is small enough and light enough to qualify as a man-portable, shoulder-fired weapon. However, for roles such as close support and suppression of enemy air defenses (SEAD), the possible use of unmanned aerial vehicles (UAVs) with long loiter time and appropriate weapons may be attractive.

However, if strike aircraft are forced to operate at altitudes in excess of 15,000 to 20,000 feet, pilots will frequently encounter conditions (clouds, fog, smoke, haze, and darkness of night) where visual acquisition of the target at such altitudes is not possible. In such circumstances, the trend in air-to-surface ordnance-delivery systems will be to use precision-guided weapons with terminal sensors and data links that are fired at a coordinate on the ground which has been designated by some other sensor or observer.

If this perception is taken to its logical limit, there will be no functional difference between air-to-surface and surface-to-surface weapons in the capabilities and attributes of the end-stage vehicle and warhead that impact the target. In this limit, both aircraft- and surface-launched weapons will be fired at targets that are not visually observed by the person who executes the weapon release command. In effect, sea-based multirole aircraft used for strike warfare will become a reusable first stage of a weapon launch system.

Aircraft delivery systems have the advantage that they can (for the same diameter/caliber weapon) deliver a heavier warhead payload a longer distance than a multistage rocket. However, as discussed in the section titled "Analysis of Duration and Costs for Future Navy and Marine Corps Force-Projection Mis-

sions" in Chapter 3 of this report, the panel suspects that whatever economic advantages may exist as a result of the employment of a reusable first stage (even assuming no attrition of aircraft), these advantages will be overwhelmed by the acquisition and operational costs of strike aircraft and the aircraft carriers needed to allow sea-based air-to-surface weapon delivery, in comparison to the acquisition and operational costs of other surface ships that carry an array of VLS cells and support the launch of rocket-propelled ordnance.

Emphasis on Medium- and Long-range Air-to-air and Long-range Ship-to-air Missiles

Traditionally the missiles used in air-to-air combat have been characterized as being short range (about 10 km), medium range (about 50 km), or long range (about 100 km). Although there is no rigid definition of the ranges involved, one may characterize missiles in the airborne intercept missile (AIM)-9 family and their foreign equivalents as being short range, missiles in the AIM-7 and AIM-120 family and their foreign equivalents as being medium range, and weapons with ranges equivalent to or greater than the range of the AIM-54 missile as being long range.

These designations are useful because they reflect on the way the missiles are used. A missile designated as a long-range air-to-air missile has a kinematic range capability to engage a target far beyond ranges that permit identification of the target by pilots using either their own vision or the on-board sensors available to them.

Medium-range air-to-air missiles have kinematic ranges that allow engagements at distances where target identification cannot be accomplished visually but can be accomplished by a combination or mix of electronic challenges (e.g., identification, friend or foe [IFF]), on-board tracking radars, or infrared search and track (IRST) systems. Short-range missiles are used at ranges where visual identification is generally possible.

Restrictive rules of engagement (ROEs) (such as visual identification required prior to engagement), weather, or an adversary's use of terrain to mask location tend to force air-to-air engagements into the regime where short-range weapons must be used. This situation must generally be viewed as unfortunate because simulations show that the outcome of a close air-to-air encounter that depends on many complex factors such as weapon performance, tactics, aircraft agility, and pilot training often ends in mutual destruction of both aircraft because of the true "fire and forget" nature of short-range IR-guided missiles.

With the introduction of the new AIM-9X missile, U.S. aircraft will have a short-range missile that will be comparable to or exceed the performance of the best short-range missiles currently available worldwide. For a short-range air-to-air missile, one figure of merit in an air-to-air encounter is how far away from boresight the missile can engage a target. This attribute translates to which pilot

can shoot first in a circling engagement. It has been projected that in such dogfight encounters the AIM-9X will give U.S. pilots an advantage. Although this advantage is real, it alone is not likely to provide a significant or robust margin in such encounters. As a result, the United States relies on superior training and tactics, areas in which the United States currently has an advantage.

Based on the perception that it is generally preferable to avoid such short-range engagements where the outcome is not a foregone conclusion, the panel has concluded that the pathway for U.S. air-to-air superiority resides in the maximum exploitation of medium- and long-range missiles. The major current limitation in the use of weapons of these classes is the issue of robust target identification at a distance. This limitation arises from the inadequacies of the performance of available sensors.

The panel recognizes and applauds the fact that numerous programs are under way to improve the operational performance of the airborne sensors that are used to support air-to-air combat. The advantages that may be achieved from improved sensors show every sign of being robust and of providing U.S. aircraft with an enduring advantage in air-to-air combat, particularly when networked in an airborne cooperative engagement capability (CEC) system. The panel believes that a long-range air-to-air missile development program should be initiated so as to be fielded on time to exploit this network.

Simple radar equation calculations indicate that as stealth technology proliferates, the performance of U.S. airborne early warning (AEW) radars will degrade. The problem is identical to the problem faced by the surface community in its attempts to maintain a competent antiair warfare (AAW) capability. In that community, the problem was alleviated significantly by the use of the CEC, which was based on the use of networked monostatic radars. Technology for CEC works extremely well against primitive (reduced nose on cross section only) stealth designs. The fielding of aircraft and or missiles that are characterized by all aspect stealth would degrade the performance of the CEC system. Radar designers have suggested that in the event of the proliferation of all-aspect stealth targets, radar designs might migrate to networked multistatic designs from networked monostatic designs.

The panel is reasonably confident that a partial solution to the problems caused by stealth aircraft can be achieved by the extension of CEC to air-to-air combat. Such an extension would also include a means to network the outputs of both radar and IR sensors. If the future introduction of all-aspect stealth targets begins to degrade the performance of airborne CEC, then there could be a migration to the use of networked multistatic radars that is postulated to provide greatly enhanced detection performance.

If an airborne CEC or its multistatic successor systems were available, tracks and target identification could be established at ranges great enough to allow significantly greater use of medium- and long-range missiles than is currently the case. The panel believes that as long-range tracking and target identification

capabilities evolve there will be a strong and almost exclusive emphasis on the use of medium- and long-range air-to-air missiles.

The panel is also concerned about the proliferation of increasingly capable long-range surface-to-air defenses around the world that eventually will put Navy fighter and strike aircraft, and high-value tactical surveillance aircraft such as the Joint Surveillance and Target Attack Radar System (JSTARS) at great risk. Recently, several third-world nations unfriendly to the United States reportedly acquired the sophisticated Russian SA-10 system, and they are expected to eventually buy the more advanced, long-range SA-12 that the Russians are eager to sell. Ultimately, these trends may threaten U.S. dominance in littoral regions. Dealing with these threats will require the continued availability of antiradiation missiles for air-defense suppression. A potentially valuable contributor to the counter-air mission would also be long-range, surface-based antiair missiles "forward passed" by netted airborne sensors.

Today the Standard Missile (SM) air defense system can engage aircraft out to at least 200 km from a ship, and the Navy some years ago had an operational longer-range antiair missile called the Talos and was seriously developing much longer-range systems. For the future, an attractive antiair concept might be a multimode version of the theaterwide theater missile defense (TMD) missile which could have an effective footprint of thousands of kilometers. The guidance-and-control requirements for ballistic missile defense (BMD) and antiair defense are very similar, and theaterwide TMD systems have already been proposed that would perform both missions.

Increased Role for Incapacitating and Other Special-purpose Weapons and Techniques

Traditionally, naval weapons have been considered to be ordnance devices that permitted the explosive release of chemical or nuclear energy to destroy enemy targets or personnel as a result of the effects of local overpressure, conflagration, or high-velocity fragments. Through the years, a realization has developed that there are limitations in the ability to cause a determined adversary to cease organized resistance solely by the delivery of ordnance devices. Also, in the past, inaccurate weapon delivery in urban areas caused much unintended damage to people and structures that were not the intended target for the weapon. Such collateral damage frequently served to increase the resolve of the hostile population to continue the conflict.

In the past, other approaches have been tried with limited success. Naval blockades have been used to disrupt an enemy's commerce and access to critical raw materials necessary for the continuation of conflict. Ultimately such approaches have tended to weaken an enemy's ability to continue a conflict but have not in themselves been the dominant cause of conflict termination.

In recent years, new technologies have been developed that can be used to

limit an adversary's ability to continue organized resistance and for discouraging the local populace from continuing to support the conflict. The panel believes that there is reason to expect that special-purpose weapons and techniques listed below may come to be numbered among the more important means used by naval forces to help achieve conflict termination.

Incapacitating (Less-than-lethal) Weapons

In many operations, it will be important for naval forces to have incapacitating (less-than-lethal) weapons available so that lethal weapons do not need to be employed. Such a situation might occur when large hostile crowds of unarmed people attempt to attack and overrun a numerically small unit of marines. Although a squad or platoon of marines is perfectly capable of protecting itself from unarmed crowds using the weapons with which they are equipped, it is generally undesirable for members of the U.S. armed forces to take actions that result in the killing or wounding of many hundreds of unarmed civilians.

The panel believes that the growing importance of military operations that have been characterized as operations other than war (OOTW) will result in the extensive development and deployment of incapacitating weapons. The panel believes that the capabilities of such weapons will be extended to the development of weapons and devices that have a capability to immobilize land vehicles, ships, and aircraft in addition to human beings.

Many techniques exist or have been suggested for incapacitating, channeling, or controlling large numbers of hostile people. The most primitive of these techniques involves the use of concrete barriers or rolls of concertina wire. High-pressure water cannons have also been used for such purposes. Newer approaches involve the deployment of impenetrable barriers of sticky foams or slippery films that are difficult or impossible to walk on. More speculative and probably politically and morally unacceptable approaches call for the use of infrasonic generators that induce nausea or lasers that are used to temporarily blind or dazzle hostile crowds or "paint" them to cause psychological effects. In recent years, the military value and the potential political liabilities have been the subject of much debate. The panel notes that the United States is a signatory to the treaty that bans the use of laser blinding weapons. Acknowledging the serious moral problems associated with the use of incapacitating weapons, the panel remains convinced that some of the possible weapons in this category will be developed and refined and will prove to be an essential component of the weapons available to support naval forces in situations where the use of classic lethal weapons is inappropriate.

The panel is also confident that the next 25 to 35 years will witness the development of weapons and techniques that allow the immobilization of ships, aircraft, and ground vehicles. In time of conflict, it might be important to interdict the flow of oil to or from an adversary. The sinking of a large modern tanker would cause an ecological disaster that would reflect adversely on the United

States. The panel is convinced that a multiplicity of techniques will be developed to immobilize ships without sinking them. These might include small torpedolike weapons that home on and destroy the screws of a surface ship, but otherwise do no damage. Alternate approaches might involve the use of laser dazzlers to drive personnel from the ship's bridge or the fast-rope delivery of Navy SEALs onto the deck of a ship being interdicted. Whatever techniques are ultimately developed, the Navy of the future will and should have a capability to immobilize hostile ships.

The problems associated with immobilizing aircraft and surface vehicles are more complex and the technical approaches are more speculative. They range from the placement of additives into the fuels used to propel them, to the use of electromagnetic pulses to destroy electronic components used to control them. Although the concepts proposed are not on firm technical or operational ground, the panel is inclined to believe that the importance of a capability to immobilize aircraft and surface vehicles will result in a major effort to develop it.

Techniques for Offensive Information Warfare

The panel believes that over the next 25 to 35 years the techniques that are used for offensive IW will undergo a continuous process of modification as computers, sensors, and communications continue to evolve. Although the specific techniques of offensive IW that are likely to be employed in the future may be substantially different from the techniques in current use, the purpose will be the same. If naval forces can use these techniques to destroy or degrade an enemy's databases, to deceive enemy commanders, and to exploit hostile transmissions and databases and their communication links, then an adversary's ability to continue a conflict will be degraded.

The information systems of an enemy's military command is not and will not be the only future target for IW attack. In the future, even relatively primitive societies will be dependent largely upon electronic media (telecommunications, radio, and television) for dissemination of information. In addition the computers and communication links needed to support the transfer of data to operate banking systems, to support commerce, to control internal transportation, and to maintain and operate police, public health, and resource distribution functions will represent lucrative targets for future IW techniques. Techniques for the interdiction of an adversary's communications with external sources of data and information about the disposition of U.S. forces will be critical to the outcome of any engagement or confrontation.

Finally, if U.S. forces can use IW techniques to usurp communication channels between regional or national leadership and their population base, the will of the population to support conflict can be attenuated with morphed messages based on a reconstruction of the recorded phonemes of the voices of the adversary's leadership.

The beneficial value of offensive IW techniques in the achievement of rapid conflict termination is limited only by one's imagination and by the technical ability of U.S. forces to gain access into the relevant systems of an adversary. The panel foresees that the naval forces, as a preconflict, forward-deployed, on-scene force, will become one of the prime users of the techniques of IW. Some IW techniques can only be executed from a platform at sea. For other techniques, only a naval platform has the capability to loiter in a position that provides the unique or optimal geographic location for the execution of offensive attacks. Overall within the next 25 to 35 years, offensive IW techniques are expected to evolve into one of the Navy's important and effective weapon systems.

In any given conflict, the use of offensive IW techniques will be strictly controlled by the theater commander in chief (CINC). Neither the Air Force, the Army, the Navy, or any other government agency can operate autonomously in this area. For many offensive IW actions, even the theater CINC must request review by the Joint Chiefs of Staff who in turn must get a release from either the President or the National Security Council. The armed services and other agencies are participants in the process to the extent that they possess the offensive IW tools and platforms to help the CINC execute his war plans.

Infrastructure Attack and Disablement

During World War II, allied forces attempted to destroy Germany's ability to wage war by a sustained and massive series of bombing raids aimed at the destruction of the infrastructure of the German economy. Although these raids did not in themselves completely destroy the German infrastructure over a period of several years, they certainly resulted in a substantial weakening of Germany's ability to prosecute the war.

Postwar surveys indicated that the main reason the bombing campaign failed to achieve its objectives more rapidly was that the weapons used in that campaign were not appropriately designed for the purpose. Most weapons dropped on Germany in World War II were bombs and incendiary devices. The dispersion associated with World War II bomb delivery meant that, statistically speaking, the critical elements of an individual factory or other economic activity were rarely destroyed or damaged. If damaged they could frequently be made operational again in a relatively short time. German use of concealment, camouflage, and deception (CCD) was also highly effective.

Modern theories of infrastructure attack start with the premise that the physical structure that supports a nation's economy is a network of nodes and services. A nation's electrical and power distribution system is generally central to the functioning of a modern economy. The panel believes that weapons and other techniques can be developed to allow the selective disablement or destruction of power generation and distribution systems. Improved techniques and weapons can be developed for the destruction of critical transportation nodes such as

bridges and tunnels and prevent internal transport of food, raw materials, and military equipment. If desired, weapons can be developed to destroy water purification and distribution nodes as well as sewage processing plants.

The panel believes that weapons and techniques currently under development will lead to a robust naval force capability for the selective and effective attack on an adversary's economic infrastructure. These techniques will be used extensively by the naval forces as their contribution to the rapid termination of a conflict.

New Techniques and Devices for Conflict in Urban Areas

Without significant changes in current weapons and sensors, warfare in urban areas will continue to be difficult to execute and will probably continue to result in significant casualties in the attacking forces. Urban buildings are, in effect, natural fortifications. The destruction of individual buildings by bombs or artillery generally serves to create rubble and in effect to improve the strength of defensive positions.

The panel does not foresee any single or simple solution to the problems associated with urban warfare. Present and foreseen technology does allow one to hold out hope that over the next 25 to 35 years, new sensors and weapons will be introduced that provide considerable advantage to attacking forces.

The first of these advances is likely to be in the area of sensors. An ability to see what is in the next building or is lurking at the next intersection without exposing our own personnel to hostile fire is of critical importance in an urban combat situation. Contemporary technology permits the development of IR, optical, and acoustic sensors that are mounted on small lightweight robots with sufficient connectivity to allow report back of the images seen. Although structure-penetrating radars have been pursued in the past with limited results, sensors could be developed that can tell forces engaged in urban combat who, or what, is in the next room or in the building across the street. Sensors could also be developed that locate the position of a mortar in defilade behind buildings by the detection and tracking of its trajectory or by use of the detection of ultraviolet (UV) flashes associated with muzzle blasts.

Although sensors will help locate hostile military forces, weapons or explosive emplacements are needed to drive out the defenders. Simple explosives are used to create passages through walls that partition the individual buildings in a city block. Once off the streets and into buildings, attacking forces clear defending personnel with automatic rifle fire, smoke, and concussion devices. Nonlethal weapons may also be useful, since they do not require line of sight (LOS).

In the future, the panel believes that robotic devices will be used to cross the next street, enter the next block of buildings, and emplace explosives against critical structural support columns and to detonate concussion devices that will stun or blind the defenders. These devices may be small tracked or wheeled

vehicles or they may be miniature UAVs. Such miniature UAVs might be able to hover on a window sill and look inside, report back what is seen, and then, on command, fly in and explode a grenade-sized weapon. Other devices that allow rapid concrete breaching and tunneling under streets and beneath buildings will allow the placement of explosive charges that will destroy strongly defended structures that cannot be cleared without excessive casualties.

New Offensive Mine Capabilities

Sea mines and land mines have long been in the operational inventory of naval forces. Modern technology provides the prospect of increasing the effectiveness of such devices significantly. In the past, mines were (with the exception of CAPTOR-like devices) essentially point contact devices. Anyone wishing to traverse a suspected minefield was faced with the fact that the probability of crossing the minefield without casualties was less than unity but not always prohibitively large. The options were either to hunt out and subsequently avoid and/or remove the mines or to penetrate the field and accept the casualties that occurred.

Modern concepts for minefields are such that attempts at penetration should (until the number of mines has been depleted by effective kills) result in high levels of lethality for the intruding force. The current and anticipated trend in minefield design is to depend on distributed and networked sensors that actuate mobile mines. In an undersea minefield, the sensors might be linked by acoustic modems. In a battlefield minefield, the sensors might be linked by IR, radio-frequency (RF), or high-frequency acoustic links.

In a statistical sense, the distributed sensors would cover 100 percent of the area where an attempt was being made to deny the adversary passage. Networking of the sensors would permit detection location and tracking of the penetrator. When the data-processing devices that control the weapons in the minefield "decide" that the penetrator warrants being attacked, a prepositioned mobile weapon is released to attack the target. Underwater, the weapon might be a high-speed rocket or torpedo. On the battlefield, the weapon might be rocket or mortar propelled.

The effectiveness of a minefield that is controlled by networked sensors would be extremely high. For example it could be used to blockade an enemy's naval forces in harbors and to interdict the enemy's seaborne commerce. To the extent that absolute denial of seaborne commerce and denial of the use of naval platforms contribute to limiting an adversary's ability to continue a conflict, minefields that are controlled by networked sensors will become a very effective future weapon system in the hands of the naval forces.

A New Approach to Very Shallow Water and Surf-zone Mine Countermeasures

Hostile mines become a weapon problem when, because they cannot be expediently found and neutralized, they cause surface forces to stand off at sig-

nificantly greater distances from a hostile coast line than they would if mines were known not to be present. An increased standoff distance will force the use of weapons with maximum practical ranges. In turn, this will have a significant impact on the distribution of weapons within the inventory of both air-to-surface and surface-to-surface weapons. Long-range missiles are generally more expensive than shorter-range missiles with comparable performance. Thus, lack of a satisfactory resolution of the mine problem will have an impact on the weapon loadout of future combatants and will require a preferential investment in longer-range weapons with the consequential result that fewer overall numbers of weapons will be able to be procured.

Before the Marine Corps metamorphoses into the mobile, lethal, stealthy combat teams envisaged for 2025 and beyond, which are fully supported by sea-based firepower and logistic support, it will be necessary to go through a transition phase. In this transition phase, the institution will learn to gain faith in its sea basing and gradually thin its land-based firepower component. For the next quarter of a century, some form of the surface assault will remain. One must address problems associated with mine countermeasures (MCM) needed to protect the forces conveyed by advanced amphibious assault vehicle (AAAV) and landing craft, air-cushioned (LCAC).

Today's MCM is slow and dangerous, consumes too many amphibious ready group (ARG) assets, and gives away any hope of tactical surprise. If the target is an island, has a small coastline, or only has a few valuable centers of gravity, avoidance may not be possible. In addition, it is not tactically wise to let an enemy use mines to force you into approach lanes of his choosing.

The panel concluded that MCM should be positive, violent, and rapid in nature. Assault forces should assume mines are present and attack accordingly. The attack should be based on a layered thinning process. The initial thinning can be done by bottom-crawling robotic explosive carriers that recognize manmade material placed where natural things should be. The robotic devices can be delivered by large unmanned undersea vehicles (UUVs). At a given time, an acoustic signal detonates all the robots and the assorted manmade objects they have found. Some mines and obstacles will die. As the sand and seawater mist settles, the second attack by long-range bomber aircraft should be executed. A mixture of explosive nets and precision-delayed fuse bombs should constitute the weapon set for the second mine- and obstacle-thinning operation.

The panel also believes that surf channeling, which is the use of a pattern of buried explosives delivered by air that clears a mine- and obstacle-free channel via cratering in the sandy bottom of the surf leading to the beach, is a viable technique. The explosive charges would destroy some of the mines and obstacles; other mines may be exposed for easy cleanup operations (or avoidance); and some would be thrown aside out of the channel. The channel would extend onto the bare sand far enough to allow for the establishment of a beachhead that is mine-free and away from the surf. The width of the channel would need to be

sufficient for modern amphibious assault craft. This would probably mean that two rows of explosive charges (~1,000 lb) with a spacing of about 10 meters would be required. The length of the rows would depend on the slope of the sandy bottom of the beach surf.

A compelling reason to use this approach for beach assault preparation is the speed with which this method could be applied, thereby depriving ground defense forces of time for in-depth preparations. Taking advantage of the element of surprise, troops in amphibious assault vehicles could quickly follow the explosions.

After the first two thinnings have been delivered by systems designed to handle and deliver ordnance, the first wave of AAAVs arrive, stop, and go through their land-configuration metamorphosis. These lane proofers are robotic vehicles with no seats, no turrets, no mission equipment, and no Marines. Each AAAV(R) (robotic) drops two anchors and proceeds ashore on its assigned GPS/IMU course. The anchors drag out the two huge line charges, which fill the AAAV(R)'s interior. The tractors swim and crawl through the twice-attacked minefield. At the end of the charges, two squibs pull and in seconds, the lane proofing charges go off. The succeeding waves of Marine-bearing AAAVs will have no trouble navigating the huge water-filled ditches made by the AAAV(R)s. It remains to be seen if the violence of the thinning and proofing attacks will also provide lanes wide enough for the LCAC waves. Tests and experiments will be required to gather hard data.

Development of Additional Types of Weapons for Nuclear and Nonnuclear Attack on Critical Hard Targets

The U.S. Navy currently operates a dedicated fleet of nuclear-powered ballistic missile submarines (SSBNs) equipped with long-range ballistic missiles and nuclear warheads. As this force ages over the next 25 to 35 years, it will need to be phased out and/or replaced.

The panel believes that, if the United States elects to replace the current sea-based nuclear force, as it is phased out of service, the weapons that will be selected may be significantly different from the currently operational weapons.

Many things have changed since the architecture of the current Navy SSBN force was established. The force was designed primarily as a survivable deterrent force. The panel believes that over the next 25 to 35 years, the primary target set for sea-based nuclear weapons will be hardened (or hard to destroy) repository sites where hostile adversaries store chemical, biological, and or nuclear warheads, and C^{4}I facilities.

To some extent, the weapons employed against this target set will depend on the attributes of the hardened or buried target. If the target is in an isolated area and is thought to be a storage site for WMD, the use of earth-penetrating low-yield nuclear warheads might be considered to be politically acceptable by our national leadership. Weapons can now be guided reliably to their intended tar-

gets with essentially zero CEP. The value of high-yield warheads (say, > 100 kilotons) will diminish. Accurately emplaced low-yield nuclear warheads should be competent to attack what the panel believes will evolve into the principal (and possibly only) target set requiring such nuclear weapons. As discussed above, U.S. options for the use of even low-yield penetrating nuclear weapons may be negated by an adversary's placement of storage sites for chemical, biological or nuclear weapons beneath inappropriate targets such as hospitals, schools, and orphanages.

Implications of Foreseen Changes in Offensive Weapons

- Development of a family of surface-to-surface precision-guided tactical ballistic missiles
  - —Shift of strike and fire-support weapons to surface-to-surface weapons
  - —Decreasing dependence on sea-based aircraft for weapon delivery
- Trend toward primary dependence on medium- and long-range air-to-air and long-range ship-to-ship missiles
- Expected migration of supporting fire for forces ashore from organic artillery to ship-launched weapons
- Evolution of sea-based nuclear weapons and their supporting platforms
  - —Shift to new types of strategic missiles and warheads
  - —Reduced dependence on large strategic submarines and high-yield weapons
- Trend to longer-range engagements of air targets
  - —Dependence on networked sensors versus visual detection and identification
  - —Increased emphasis on standoff aircraft and ships for air superiority
  - —Decreased need for high-performance agile fighter aircraft

Implications of the Development of a Family of Surface-to-surface Precision-guided Tactical Ballistic Missiles

The panel believes that the most significant and far-reaching changes in Navy weapons will occur in the area of sea-launched, precision-guided tactical ballistic missiles. Over time, they should begin to replace both air-breathing cruise missiles and air-to-surface missiles for strikes against both fixed and mobile targets.

The panel believes that 25 to 35 years into the future sea-based attacks on fixed remote structural targets (buildings, transportation nodes, and storage and fabrication facilities) will become the exclusive domain of long-range, precision-guided ballistic missiles. It recognizes that in times of conflict the theater CINC designates targets and the order in which they are to be attacked. Weapon choice by a CINC will be governed by many factors—possible loss of pilots and aircraft,

the probable extent of collateral damage, mission execution time, weapon capability, in-theater availability, and so forth.

A role in long-range strike missions in a threat environment will continue to exist for both manned and unmanned recoverable stealthy aircraft, when the remote target is ephemeral in nature with exposure times that are less than the time of flight of a supersonic missile from its sea-based launch point to the target location. Ultimately in such situations, long-endurance, stealthy, recoverable aircraft (manned aircraft or UAV) equipped with short-range, high-speed missiles will loiter near the expected target exposure sites. They may be equipped with sensors that will allow the detection of a target as soon as the target leaves its concealed location. When UAVs are used for such missions, they will be equipped with data links that allow weapon release by a person in the loop.

The panel believes that the most significant impact of the transition of offensive operations from a predominantly carrier-based air strike force to a combined force that includes a missile strike force-based weapon launch from vertical launch system (VLS) tubes.

Implications of the Trend Toward Primary Dependence on Medium- and Long-range Air-to-air and Long-range Ship-to-ship Missiles

The panel believes that future aircraft will become multirole platforms that are designed for launching medium- and long-range missiles and for other multirole functions, including strike, SEAD, reconnaissance (RECCE), and EW, and will not be optimized for their agility in dogfight situations. Their designs should end up being significantly at variance from the designs of current and near-term air-superiority fighters.

Although the analogy should not be taken literally, one may think of current and next-generation fighters as being "souped-up sports cars." Future aircraft performing an air-superiority mission will dominate their adversaries at medium and long standoff distances and may be thought of as "pickup trucks." As such, the multirole platform would need the best available stealth capability, and it could be equipped with the complex computational system that permitted it to serve as receive node in a multistatic radar system. Since the future platforms would be a participant in a sophisticated network of sensors, its data links and data-processing capability would be many orders of magnitude greater than the capability incorporated into current fighter aircraft. What this aircraft lacked in acceleration and agility would be more than made up for in the range advantage of its on-board and off-board sensors and its weapons.

Likewise, the capability of future long-range ship-to-air missiles would be enhanced by advanced command, control, communications, and intelligence (C^3I) capabilities such as the Navy's new CEC system designed for defending against TBMs and air-breathing targets at sea and over land in littoral areas. The aircraft

and ship long-range antiair systems would complement each other, often with synergistic results. The future fighter, for example, could markedly extend its firepower by calling for the ship long-range interceptors and then forward-passing them into the target area. In circumstances where an airborne capability is unavailable or the risk of its use is too high, the shipwide area AAW might serve as an effective backup or standalone alternative.

Implications of the Expected Migration of Supporting Firepower for Forces Ashore from Organic Artillery to Sea-launched Weapons

One major foreseen impact of the development of improved sea-based firepower is in the area of combat weapons that will be organic to future amphibious landing forces. Because of the tremendous firepower that should be available on call to engaged forces ashore, their organic assets such as tanks and artillery will, over time, show a reduction in the logistic load needed to support engaged forces ashore.

The panel believes that sea-based firepower is the key to the reduction of the logistic tail of engaged forces ashore, if, as is believed possible, the commander of an engaged company or battalion can call for, and immediately receive, sufficient and appropriate fire support to allow him to accomplish his mission. To satisfy this requirement, the Navy must provide the landing forces with the equivalent of arsenal ships that have the necessary depth of magazine and rate of fire to satisfy the needs of the engaged combat commander. As discussed above, the use of double-stacked loadouts of small diameter missiles in VLS tubes will do much to increase the sustainability of fire support ships. Accordingly, the panel believes that the need for high-capacity launchers will drive the design of future weapons platforms.

Implications of the Evolution of Sea-based Nuclear Weapons and Their Supporting Platforms

The design of currently deployed sea-based nuclear weapons was strongly influenced by the location of the target set they were built to destroy and by the requirement for assured survivability of U.S. sea-based nuclear forces. The choice of the D-5 design with the extended range it provides was driven by the desire to make the ASW problem as difficult as possible for the U.S. then adversary, the Soviet Union. The greater the range of the D-5, the greater the area over which the Soviets would be required to exert an effective ASW capability. The introduction of the D-5 allowed a total patrol area for SSBNs large enough to render any conceivable Soviet ASW actions ineffective and thus to assure the survivability of U.S. SSBNs.

Weapons with ranges of only 2,000 to 3,000 kilometers will generally permit most conceivable future targets (there may be a few limited exceptions for remote parts of China, Kazakhstan, and Siberia) to be attacked from the sea. If it is

desired to attack a target located deep within a continental land mass with a submarine-launched ballistic missile with a range of 2,000 to 3,000 kilometers, the submarine will be forced to make a close approach to an appropriate coast line. For example, a 3,000-km missile may be used to attack targets in western China if it is launched from the extreme northern end of the Bay of Bengal.

The real issue in the selection of the range of a potential future sea-based missile is whether the United States will assume that any future adversary that is a potential target for nuclear attack will have an ASW competence that will force future SSBNs to longer standoff ranges (and longer weapon ranges) to assure mission success. While the panel has not examined the ASW problem in detail,[1] it believes that the Navy's SSBN forces are now and will continue to be relatively invulnerable to any postulated ASW capabilities of our most likely adversaries. Consequently, the panel believes that, if a decision is made to replace the D-5 missiles at the end of their service lives, the replacement missile will have a range that is significantly less than the range of the D-5.

The panel believes that the traditional Cold War target set for the nuclear warheads carried by the SSBN force will decrease in the future and that ultimately (possibly within the 35-year horizon of this report) the future use of U.S. sea-based nuclear weapons may be limited to hardened storage sites for an adversary's chemical, biological, and nuclear weapons.

Most of the ensemble of possible future targets appears to require relatively low-yield, earth-penetrating warheads carried on missiles that have essentially zero CEP. The panel believes that for what appears to be the most likely future target set, the required range of sea-based nuclear weapons will be only about 2,000 to 3,000 kilometers. The resulting missile will be very different from the configuration of existing D-5 missiles and will not necessarily be tied to a unique single-purpose platform such as the SSBN class of submarine. At a minimum, it is unlikely to have the same diameter as a D-5 missile.

The current SSBN weapons carry multiple independently targetable reentry vehicles (MIRVs). An enormous operational inflexibility is incurred by the exclusive loading of MIRVed missiles in the force. In any future study of a replacement for the D-5, an appropriate topic for consideration might be whether or not the United States should change entirely to single-warhead missiles, especially in view of the much reduced cost of guidance systems, the possibility under almost all circumstances of GPS guidance, of strategic missiles, and so on.

Although the panel is suggesting that the new types of delivery vehicles for nuclear warheads will enter the sea-based nuclear inventory, it is not suggesting that nuclear capability will be proliferated across the fleet. The panel foresees the

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[1]Reports from the Panel on Undersea Warfare (Naval Studies Board. 1997. *Volume 7: Undersea Warfare, Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st-Century Force,* National Academy Press, Washington, D.C.) and the Panel on Platforms (*Volume 6: Platforms* of the same series) contain discussions of the ASW problem and maintenance of U.S. submarine stealth.

continued existence of platforms that are designed only for the delivery of nuclear weapons. However, as the weapon loadout changes, the design of SSBNs may change. Instead of being a completely large-hatch vessel designed to launch D-5 type missiles, future SSBNs might be mixed small- and large-hatch vessels or they might be exclusively small-hatch vessels. In view of the uncertain future of the process of evolution/elimination of sea-based nuclear weapons, the panel does not anticipate any radical redesign of SSBNs in the next 10 to 15 years. The panel did not attempt to assess the treaty implications of fielding a new family of platforms designed to counter a target set other than the classic target set of remote Russian missile silos.

DEFENSIVE WEAPON SYSTEM CONSIDERATIONS

In addition to foreseen changes in the capabilities of future offensive weapons and the changes that are likely concomitants of their introduction, major impacts on the naval forces will arise from the need for enhanced defensive capabilities. Unless these defensive needs are met, the threats involved will make it difficult for the naval forces to project power with acceptable losses and to control the seas in regional crises. The areas of concern that the panel believes will require both improved technology and a significant capital investment are as follows:

- Tactical ballistic missiles with WMD—unless competent defense is available, U.S. theater operations could be constrained by the potential for unacceptable losses.
- Low-observable (LO) sea-skimming antiship missiles (ASMs)—the capability to detect, track, and kill stealthy missiles at ranges essential to the success of sea control and power projection is necessary.
- Quiet submarines—competent ASW and own-ship torpedo defense are essential to the success of sea-based power projection.
- Shallow water mines and land mines with improved technology
  —Serious deterrent to amphibious and littoral operations; and
  —No completely satisfactory solution foreseen.

The principal areas of concern are ballistic missiles, particularly those with warheads that carry WMD, advanced LO sea-skimming cruise missiles, quiet submarines, and mines (including both shallow-water mines and land mines) as well as other weapons that employ chemical and biological agents.

Ballistic Missile Defense

The threat of TBMs is real. They were first used by the Germans toward the end of World War II as a terror weapon against allied population centers, and an updated version of the German V2 missile found similar use in the recent Gulf War. The technology of the rather primitive Scud missiles employed by the Iraqis in the Gulf War will be improved significantly over the next 25 to 35 years.

The U.S. intelligence community generally believes that, given currently available technology, it will be feasible for many of our possible future adversaries to build or acquire TBMs with maneuvering and terminally guided reentry vehicles, supported by penetration aids, that can detect and hit relatively slow-moving targets such as surface ships. Accurate attack on fixed locations is a certainty. Accurate conventional attack would have made the Scuds a much more serious military threat in Desert Storm. The warheads of such TBMs may incorporate chemical, biological, or nuclear payload, the so-called weapons of mass destruction. Any defense against the TBMs will be further complicated by an adversary's use of fractionated or submunition warheads that can be deployed before the TBM apogee or even shortly after the booster burns out.

Unless the naval forces have a competent defense against future TBMs, the availability of such weapons in the hands of future adversaries probably would serve as a deterrent to or constraint on U.S. littoral operations. The unanswered threat of ballistic missiles—with or without WMD—might cause an amphibious landing and land attack to result in unacceptable rates of casualties. As discussed in detail later in this report, the Department of the Navy is pursuing what the panel believes is an appropriate evolutionary approach to TMD, starting with short-range terminal defense (also called area or lower tier) based on existing Aegis ships and their standard missile antiair system. However, if the incoming missile deploys its decoys and reentry vehicles prior to apogee, the problems of terminal defense will become quite difficult, particularly if the reentry vehicles are able to maneuver. Therefore, plans are to evolve to long-range TMD (called theaterwide or upper tier) that would have the capability to engage TBMs in their ascent phase (i.e., post boost but prior to apogee). This program appears to be on track with a reasonable probability of success. The panel is aware that this approach will have problems with TBMs that are able to deploy penetration aids early in their ascent phase.

The Navy Department currently has no plans to attack TBMs in their boost phase. The panel believes this could be a serious gap over the next 25 to 35 years as TBMs increasingly will be able to deploy large numbers of chemical, biological, explosive, and inert submunitions shortly after boost. Several boost-phase intercept (BPI) concepts were and are being investigated by the Air Force and the Ballistic Missile Defense Office (BMDO), such as an airborne-based laser (ABL) and the deployment of forward-deployed loitering weapons designed to detect and attack TBMs early in the boost phase. Unless laser technology changes radically, the panel is not sanguine about the possibility of building a boost-phase laser weapon that will be small enough to be carried by a carrier-based aircraft—manned or unmanned. Forward-loitering weapons are certainly feasible, but their employment from naval platforms would be difficult with today's technology and ship designs. Diode-pulsed solid-state lasers offer the best hope of a laser system for antiair purposes. The first development of such a system might be for close-in defense. As lethality, weight, and volume improve, a longer-range counter-air or counter-missile system may be feasible. The panel believes sea-

based BPI merits further evaluation because of the future need for an organic on-the-spot system deployable from Navy ships that often will be the first on the scene in a fast-breaking regional crisis.

Low-observable Sea-skimming Antiship Missiles

There is every reason to believe that for the indefinite future, LO sea-skimming antiship missiles (ASMs) will continue to proliferate around the world and will continue to constitute the most serious threat to surface platforms operating in the littoral zone. A robust defense against such missiles will be essential to the Navy's success in both sea-control and power-projection operations. The key to the defeat of such missiles will be a capability to detect and track them at extended ranges.

The Navy's newly introduced CEC, which is basically a network of monostatic radars, has proven to be extremely effective against first-generation LO targets that have small retroreflective radar cross sections (RCSs) in the nose-on direction but have significant cross sections when viewed from other directions. If more sophisticated stealth designs can be implemented, then missiles with reduced radar reflections at all angles of observation may begin to appear. Missiles with reduced all-aspect, all-frequency RCSs may begin to become operational 25 to 35 years into the future and relatively common throughout the world. If this happens, the performance advantage of the CEC and the Navy's defense against ASMs may be expected to degrade.

Extensive efforts have been under way to find a means of countering LO targets including advanced missiles and gun systems and directed-energy weapons. Most of the approaches that have been investigated envisage the use of complex systems that have proven to be difficult to implement. If a usable counter-low-observable (CLO) system cannot be fielded and the performance of the Navy's CEC system is degraded by the introduction of all-aspect, all-frequency LO missiles, then the Navy will probably tend to position its surface ships at greater standoff ranges from the shore than those currently employed. This in turn would imply that surface ships primarily would tend to use large long-range missiles. Shorter-range missiles designed to attack mobile tactical targets would have to be launched from submarines or long-range aircraft.

Quiet Submarine Threat

In *Volume 7: Undersea Warfare*,[2] the issues associated with the present and expected further proliferation of modern quiet submarines are discussed in detail. Without competent antisubmarine warfare (ASW) and own-ship torpedo-defense

[2]Naval Studies Board. 1996. *Volume 7: Undersea Warfare, Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st-Century Force,* National Academy Press, Washington, D.C.

capabilities, both sea control and sea-based projection of power become questionable operational concepts.

Traditionally, ASW has involved the detection of submarines and the delivery of weapons designed to sink them. In addition, ASW may also involve the deployment of offensive minefields designed to prevent submarines from leaving port. The specific issues related to the detection of quiet submarines are discussed in *Volume 7: Undersea Warfare.*

ASW weapons are generally of two types—heavyweight (21-in. diameter) submarine-launched torpedoes and lightweight aircraft-launched torpedoes. Although excellent weapons for deep-water engagements currently are deployed in the fleet, they are subject to various forms of negation and consequently their performance will need to be improved if the U.S. Navy is to retain an effective ASW capability, particularly in the littoral. The principal deficiency affecting ASW weapon performance is the capability of the weapon to acquire and home on a quiet, modern submarine operating in the complex, acoustic environments of the littorals and making use of sophisticated antiweapon countermeasures. Advances in weapons sensors and processing technology are needed to improve the detection of LO targets, classify against false contacts, and cope with a highly variable, acoustic situation driven by the natural environment and advanced countermeasures.

In its considerations of ASW weapons, the Panel on Weapons found that a considerable array of technology opportunities are either being pursued or can be pursued that should provide near-term insertion candidates for upgrading the present system. These improvements could form the basis for significantly advanced, future weapon capabilities. To improve detection and homing on littoral environs, research efforts are under way that permit and exploit a significant expansion (by factors of 20) of the sensor and processing frequency bandwidth. Increased energy and power density provided by advanced, metal-reacting approaches coupled with supercavitation hydrodynamics set the stage for substantial gains in speed and endurance for weapons and UUVs. Research is currently under way that, if successful, will increase the explosive yield and effectiveness of the warheads of lightweight torpedoes and improve the terminal guidance.

The quiet threat can be mitigated in several ways. Connectivity between sensors, platforms, and weapons will increase the probability of detection and tracking of quiet submarines. A complementary response would be to develop and deploy technologies that will negate their weapons. Torpedoes can be negated by the deployment of countermeasures that defeat the torpedo's sensors and guidance systems. As discussed in detail later in this report, such countermeasures have been employed with varying degrees of effectiveness for many years.

The panel has concluded that a more robust solution to the problem of torpedo defense would be available with the development of an antitorpedo torpedo (ATT). The panel believes that the technology for an ATT now exists, and if the application of this technology results in the deployment of an operational

weapon system, survival of surface ships and submarines in a torpedo attack will be greatly increased.

An additional approach for countering a surprise attack from a quiet submarine would be the development of a rapid-response weapon that offered quick reaction time and fast runout speed to forestall attack.

Shallow-water Mines and Land Mines

The use of shallow-water mines and land mines as defensive weapons is discussed in detail in Chapter 8 of this volume.

2

Technology Drivers

In the nine-volume study of which this report is a part, the overall implications of technology are reviewed in *Volume 2: Technology*.[1] However, technology developments that are fundamental to presumptions about the future evolution of weapons are reviewed in this chapter. Based on an assessment of the relative advances that might be achieved in some of the areas of technology reviewed below, the panel concluded that significant changes will occur in the configuration of sea-based weapon systems of the future.

EXPLOSIVES AND PROPULSION

Explosives Science and Technology

Background

Although the knowledge and use of explosive substances go back many centuries, the overwhelming percentage of our understanding of the science and technology of explosives is far more recent. The rapid expansion of knowledge of organic chemistry and chemical bonding in the 19th century resulted in the synthesis of tens of thousands of new compounds, among them many explosives. Increasingly sophisticated understanding of physics, thermodynamics, and chem-

[1]Naval Studies Board. 1997. *Volume 2: Technology, Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st-Century Force,* National Academy Press, Washington, D.C.

istry opened the way to theoretical understanding of explosive phenomena in the 20th century, and the concurrent development of testing techniques and instrumentation permitted the generation of data on the basis of which theories could be developed, rejected, modified, or expanded.

The pressures of World War I led to major advances in the development of explosives and their application in artillery and other relatively demanding devices of the day. Thus, amatols, ammonium picrate (explosive D), and many other explosive compounds and mixtures were employed by one or the other of the belligerents. Germany, pressed as it was by the Allied blockade, was particularly active in experimentation. Nevertheless, it is interesting that TNT and mercury fulminate continued as major military explosives right up to World War II.

World War II saw the extensive application of important explosives such as the nitramines (notably RDX and HMX) to military use. Even more dramatic was the evolution of the modern understanding of detonation and the truly effective application of the detonation process to the needs of warfare. Again, under the pressures of war, a greatly expanded working force (including many of the most illustrious scientists of the period) made enormous strides in virtually all areas of explosive science and technology.

The great strides of the World War II years continued on into the later 1940s, early 1950s, and beyond, resulting in a number of developments. For instance, remarkable temperature-resistant and high-energy-density explosives have been synthesized; the field of plastic-bonded explosives (PBXs) has developed; energetic binders and thermoplastic elastomeric binders have been introduced; the ability to fracture, accelerate, shape, and form metal has been enormously extended; important advances in energy release and use of available energy have been achieved for underwater explosives; and steady advances have been made in our basic knowledge of explosive stability and detonation.

Although the three U.S. Services have benefited from these explosive developments in the design of weaponry, the partition of available energy for undersea weapons can be quite different for undersea targets compared with air targets. For this reason, the discussion of explosive technology development, current and future, is separated into undersea weaponry and air and surface weaponry.

Explosives for Undersea Weaponry

Technology Needs

The Department of the Navy explosives science and technology (S&T) program continuously addresses the needs of undersea weaponry by providing safe, reliable, effective, and affordable explosives for use in torpedoes, undersea mines, torpedo defense counter weapons, and mine countermeasure warheads. Particular emphasis is placed on materials suitable for lightweight and heavyweight torpedoes, although the technology is spun off to other undersea weapons. The

underwater environment where these explosives perform introduces unique demands upon explosive energy release that include persistent calls for greater total energy release along with controlled partitioning of energy between shock wave and explosion gas bubble. Recognition of bubble whipping and jetting as a means of producing damage to subsurface as well as surface targets increases the urgency for development of explosives that release energy so as to contribute optimally to bubble damage. New warhead concepts intended for use against robustly constructed submarines have recently introduced new requirements for insensitivity to be designed into high-performance underwater explosives.

The relatively high acquisition costs of the current Mk-50 lightweight torpedo and Mk-48 heavyweight torpedo have driven the Navy to a hybrid lightweight torpedo using less expensive Mk-46 torpedo components (including a small explosive warhead) along with critical Mk-50 components, such as the guidance and control (G&C). In the near term, multimode type warheads are envisioned that use sophisticated fuse initiators to drive shaped-charge jets, as well as to initiate bulk explosions with increased energy release. In the long term, an explosive with two to three times the energy release of current underwater explosives (PBXN103) is needed to counter the robustly constructed submarine threat with affordable, volume-limited, and safe underwater weapons.[2] Such an advance in energy output is also needed for more effective sea mines, improved countermeasures for torpedo defense, and neutralization of enemy sea mines and anti-invasion mines.

Current Status of Undersea Explosive Technology

Figure 2.1 shows the Navy underwater bulk charge explosive development history from 1900 to the present in terms of energy release including shock and high-bubble energy (HBE). State-of-the-art technology in bulk charge explosives is represented by the compositions PBXN-103, PBXN-105, and PBXN-111 currently in Service use. Important improvements in both performance and insensitivity appear possible through use of ingredient combinations that react with high efficiency and contain much more chemical energy. The major issues in bulk charge explosive development are energy/insensitivity tradeoffs and energy release rates (energy partitioning between shock and bubble) during underwater explosion events.

Within the ongoing science and technology program, HBE explosives are being developed. For example, an ammonium dinitramide (ADN) explosive was developed that will provide 50 percent more bubble energy than is currently available from the best performing underwater explosive (PBXN-103).[3] This

[2]Goldwasser, Judah. 1996. "Undersea Warheads and Explosives," Office of Naval Research, Arlington, Va., presentation to the Panel on Weapons, May 13.

[3]Miller, Richard S. 1996. "Energetic Materials, Concepts, Technology," Office of Naval Research, Arlington, Va., presentation to the Panel on Weapons, May 13.

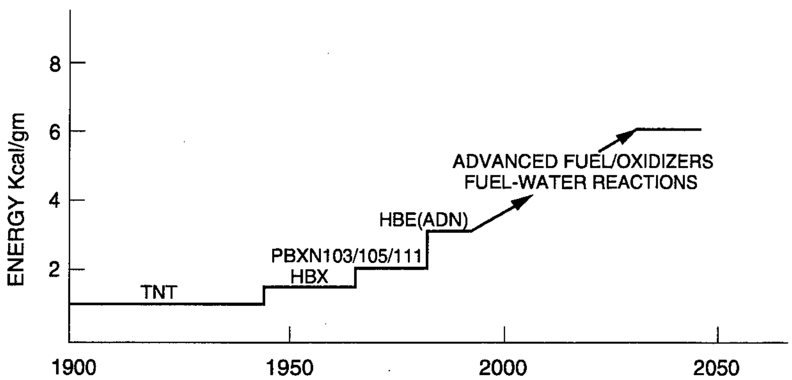

FIGURE 2.1 History and projection of the energy release from underwater explosives.

will significantly increase the lethal radii of volume-limited underwater weapons. A 50 percent increase corresponds to about a 25 percent increase in lethal radius.

Historically, a favored way of increasing bubble energy is by the use of a metal (usually aluminum) in the explosive composition. The energy provided by the reaction of the metal with detonation products (H_2O, CO_2) is greater on a volume basis than the energy of the explosive displaced by the metal, so metallized compositions can give hotter gases and, thus, larger bubbles for the same number of moles of gaseous products than can nonmetallized explosives. PBXN-103, the major underwater explosive currently in Service use, is an aluminized explosive. Suggestions for explosives to provide near-term performance improvements beyond PBXN-103 include strategies ranging from enhancement of the reactivity of aluminum to total or partial replacement of the aluminum with more thermodynamically attractive materials, such as zirconium, magnesium, or boron.[4]

Explosive Science and Technology Projections for Undersea Weaponry

Significant advances in total chemical energy from underwater explosions (see Figure 2.1) are expected to be achieved through development of additional fuel/oxidizer arrangements, through development of ways to use other fuel sources such as residual fuel and/or products from torpedo propulsion, and through development of methods to make use of sea water as an oxygen source for the explosive reaction. Efforts under way in new oxidizers, novel fuels such as boron, hafnium, coated metals (magnesium on aluminum and titanium on boron), nanosize metals, and new binders offer the potential of increasing the energy release by a factor of three compared with that of the current PBXN-103.

[4]Goldwasser, Judah. 1996. "Undersea Warheads and Explosives," Office of Naval Research, Arlington, Va., presentation to the Panel on Weapons, May 13.

Ideal components such as RDX, HMX, energetic binders, and the like are added to ensure that the explosive mixture can be detonated. Metal fuels are added to increase the heat of reaction per unit volume, and oxidizers are added to complete the oxidation of the metal fuel. Key technologies that should be continued are illustrated in Table 2.1, which provides an assessment of candidate energetic materials that also include energy performance gains, impact on Navy capabilities, risk, and approximate time frame.

An example of a fuel element that shows promise in the formulation of explosives for underwater application is boron. Although the energetics of the boron water reaction look very good thermodynamically, early research in the area of boron-containing explosives was not very fruitful because of the poor efficiency of the oxidation in the presence of hydrogen-containing species such as water. Rather than going to B_2O_3, the boron ended up in lower energy intermediates such as HOBO (HBO_2).[5] Recent advances in the use of boron in solid-fuel ramjet propellants have achieved efficiencies exceeding 90 percent in combustion of boron. Because the technology associated with boron combustion has advanced considerably since the time when the research into boron-containing explosives was focused on variations of the HBX series of explosives, investigations into boron-based explosives, as well as other metallized formulations, should be continued.

Although substantial improvements in energy release might be expected from fuel-water or fuel-oxidizer reactions, partition of the energy must be considered. It is expected that any energy that can be gained from fuel-oxidizer reactions will contribute more to the bubble energy than to the shock energy, since the time scale of the reaction will be comparatively large, owing to the necessity of the fuel coming into close proximity with the oxidizer before reaction can occur. It is also known that there is limited time available for production of energy that can contribute to the bubble. Research in explosive formulations is investigating ways of partitioning the energy. In addition, the evolution of sophisticated modeling and simulation of target structural response should provide guidance as to how to partition the energy to maximize target damage.

The development of nanosize metals such as aluminum[6] should be continued as a possible means of increasing the rate of reaction and energy level. Underwater explosives exploit aluminum for its conversion to oxide through the consumption of oxygen from the water. It is expected that through the increased intimacy of contact and/or higher surface area afforded by the nanosize aluminum, increased release rates and complete consumption of the aluminum will result.

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[5]Joint Army, Navy, NASA, Air Force (JANNAF) Interagency Propulsion Committee meeting, documented by Chemical Propulsion Information Agency, Johns Hopkins University, Columbia, Md. Available at Web site: http://www.jhu.edu/~cpia/jannaf/index.html.

[6]Coffey, C.S., and R.A. Brizzolara. 1993. "Nanophase Aluminum for Potential Applications to Improved Explosives," *NSWC Technical Digest*, September, pp. 94-101.

TABLE 2.1 Candidate Energetic Materials Assessment

	Undersea Weaponry			Air and Surface Weaponry		
Energetic Materials System Attributes	New Fuels (B, Hf, etc.), Coated Metals, Nanosize Metals	New Oxidizers ADN, NF_2, TNAZ	Reactive Materials, TiB_2, HfB_2, TiC, etc.	CL-20 Energy Coupling Extended Solids	Solid Fuel Air Explosive	New Molecules
Targets	Submarines, torpedo defense, ships, combatants		Submarines, torpedo defense, MCM	Soft and hard land targets	Area soft-fixed, soft mobile	All
Performance gain	Energy 2 to 3 times (PBXN103)		Energy/volume 3 times TNT	Energy/volume 3 times HMX	Blast energy 3 times fuel/air	
Impact on naval force capability	Rupture all robustly constructed submarines, high-speed (200-knot) torpedo defense, small lethal mines		Burn through submarine hull, double water penetration and hole size	Precision munitions with 2 to 3 times increase in penetration	Increase in area coverage and lethality	Major impact on all weapons
Risk	Moderate		Moderate	Moderate	Low	High
Time frame[a]	Mid to far term		Mid term	Mid to far term	Mid to far term	Far term

[a]Mid term: 2010 to 2020; far term: 2020 to 2035.

New oxidizers such as ADN and NF_2 nitrate salts (analogs of HMX, RDX, and PETN) are progressing and present an opportunity for a significant increase in released energy.[7] Basic research (6.1) on new molecules is focused on realizing the high-performance potential of difluoramine-based compounds and high-nitrogen compounds. The combustion of metals with NF_2-based oxidizers is more efficient, and formulations have large increases in calculated detonation pressure and I_{SP} when compared with those of ammonium perchlorate (AP) and HMX formulations, in which metals such as aluminum and boron are not efficiently converted to their oxides. An intense effort is under way to develop these novel and promising analogs to nitramine and nitrate ester oxidizers. In the pursuit of decoupling performance and sensitivity, new classes of high-nitrogen compounds with high calculated energies, but with structural features that are designed to decrease sensitivity, are under development. These materials have potential for significant increase in detonation pressure which will significantly increase the penetration capability of shaped-charge jets in defeating robustly constructed submarines.

Reactive materials are being studied for a number of weapon concepts including shaped-charge jets and explosively formed projectiles (EFPs) for enhanced water penetration and holing of submarines, antimine munitions for destroying moored mines and sea mines, and underwater projectiles for torpedo defense. Several classes of solid reactive materials include polymers, metal/oxidizer mixtures, and intermetallics and solid materials. Reactive material mixtures may be formulated that produce exothermic energy greater than current explosives. In the near term, reactive material placed in a Mk-46 torpedo-size shaped-charge jet has the potential of doubling the hole size in even robustly constructed submarines. Some reactive materials when thermally or shock-initiated generate a tremendous amount of heat.[8] By placing a ring of reactive material around the nose of a lightweight torpedo, it may be possible to literally burn through the hull of a submarine within 1 to 10 ms.

Explosives for Air and Surface Weaponry

Technology Needs

Naval force munitions that are designed to defeat air and surface targets require a variety of explosive types. High-energy explosives that release the energy very rapidly are required for fragmenting munitions and shaped-charge weapons. Insensitive high-energy explosives are required by munitions that must penetrate hulls, armor, or other obstructions before they detonate in the normal

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[7] Miller, Richard S. 1996. "Energetic Materials, Concepts, Technology," Office of Naval Research, Arlington, Va., presentation to the Panel on Weapons, May 13.

[8] Gotzmer, Carl. 1996. "Explosives/Warhead Intermetallic—SHS and SISSR's Applications," Naval Surface Warfare Center, Indian Head Division, Indian Head, Md., presentation to the Panel on Weapons, August 6.

mode. Certain area targets are addressed by fuel air explosives that provide blast of moderate intensity over broad areas. Some advanced warhead concepts, such as the deformable aimable warhead design, introduce unique requirements for insensitivity in combination with metal driving performance.

Improved munitions/warheads are needed for weapons to counter the theater ballistic missile defense (TBMD), negate enemy C^3I, aircraft self-defense, ship defense against low-observable cruise missiles, attack deeply buried hard targets, stop invading armies, attack WMD on the ground, and retain an air-to-air combat edge.

Status of Air and Surface Weaponry Explosive Technology

Currently Department of the Navy development efforts are under way to make maximum use of HMX and RDX in cast-cured binder designs to fulfill specific requirements of weapon performance and insensitivity. Navy-developed cast-cured PBXs are the state of the art for the world. Fleet use is seen with PBXN-103 through PBXN-111. In general, to drive metal, organic explosives such as OCTOL, PBXN-110, or PBXN-107 are used. For air-blast and general-purpose applications, aluminized explosives such as H-6 or PBXN-109 are used. Table 2.2 lists PBX explosives being used in current Navy weapons and in some Army weapons. New work on melt-cast PBX technology has recently begun using thermoplastic elastomers (TPEs). TPEs in the inert version allow tailoring of melt properties so that processing is done in simple and widely available melt kettles rather than in Baker-Perkins type mixers. Current efforts involve development of explosive formulations based on TPEs filled with solids such as NTO and aluminum. NTO is a new solid explosive of moderate energy and great insensitivity and is in the early stages of development. The major issue is the achievement of advantageous insensitivity/performance combinations for explosives that will be used in naval munitions. Particular emphasis is being placed on the development of an explosive that will resist premature initiation during deformation in deformable ordnance systems (DOSs).

The Army uses large quantities of LX-14 in the main charge of their munitions to drive metal in shaped-charge jets and EFPs. LX-14, which was developed by Lawrence Livermore National Laboratory (LLNL), is about 95 percent HMX and has about 35 percent higher detonation pressure than PBXN-110 (Navy explosive) and about 10 percent higher detonation velocity, thereby resulting in better metal driving capability. LX-14 has been qualified as a booster material by the Navy, but not as a main-charge explosive because of safety concerns. The Army is currently working on an insensitive high-energy explosive replacement for LX-14 for Javelin and SADARM.[9]

[9]Pearson, J.C. 1995. "Army Anti-Armor Technology," OSD Technology Overview briefing to Mr. Richard Menz, Office of the Deputy Director for Research and Engineering, Office of Munitions, Office of the Secretary of Defense, July 10-14.

TABLE 2.2 Applications of Plastic-bonded Explosives

Explosive	Specification	Names of Related PBXs	By Warhead Function	By Warhead Effect	Status	Warhead Application
Castable PBXs						
PBX(AF)-108		AFX-108	Main charge	Low brisant, insensitive	Service approved	
PBXC-117(Q)			Main charge	Brisant	Qualified	None
PBXN-101	WS-3829	PBXC-104	Main charge	Brisant	Service approved	Strike missile
PBXN-102	WS-3823	PBXC-105	Main charge	Brisant	Service approved	Sidewinder, not in production
PBXN-103	WS-12800	PBXW-100	Main charge	Underwater	Service approved	Mk-46 torpedo, Quickstrike
PBXN-104	WS-11511	PBXC-115	Main charge	Low brisant	Service approved	Phoenix missile
PBXN-105	WS-13112	PBXW-104	Main charge	Underwater	Service approved	Mk-48 torpedo
PBXN-106	WS-13522	PBXW-106	Main charge	Brisant	Service approved	SM-II missile, High-fragment projectile
PBXN-107		PBXC-116(Q)	Main charge	Brisant	Service approved	
PBXN-109	WS-23147	PBXW-109 (Type E)	Main charge	GP[a]	Service approved	
PBXN-110	WS-22347	PBXW-113(Q)	Main/transfer charge	Brisant	Service approved	Navy warheads
PBXW-107(Q)	WS-14158		Main charge	GP[a]	Qualified	None
PBXW-108(Q)			Main charge	Brisant	Qualified	None
PBXW-114(Q)	WS-23159		Main charge	Brisant, U/W	Qualified	None
PBXW-115(Q)	WS-26580		Main charge	Underwater	Qualified	Anti-U/W mines

Pressed PBXs						
Comp A-3 (Type H(Q))		PBXW-6	Main charge, booster	Brisant		
LX-14			Army-main charge Navy-booster	Brisant	Army-Service approved Navy-Booster qualified	Hell fire missile
PBXN-1	OS-11632		Main charge	Brisant	Service approved	Missiles
PBXN-3	OS-11641		Main charge	Brisant	Service approved	Missiles
PBXN-4	MIL-P-23625	PBXC-7	Main charge	Brisant	Service approved	Missiles
PBXN-5	MIL-E-81111	PBXC-6	Booster		Service approved	Booster
PBXN-6	WS-12604	PBXC-12	Booster		Service approved	Booster
PBXN-7	WS-23160	PBXW-7 (Type II)	Booster		Qualified	Lead (Mk-50 torpedo WH)
PBXW-7 (Type I)			Booster		Qualified	Developmental warheads
Extrudable and Injection Moldable PBXs						
PBXN-201	WS-11498	PBXC-202	Booster charge		Service approved	Bomb BLU-73/B
PBXN-301	WS-12612A	PBXC-303, XTX-8003	Transfer link		Service approved	Condor, Sidewinder

[a]General purpose; blast and fragmentation (GP).

SOURCE: Anderson, E. 1993. "Explosives," *Tactical Missile Warheads*, Joseph Carleone, ed., Progress in Astronautics and Aeronautics Series, Vol. 155, American Institute of Aeronautics and Astronautics, Washington, D.C.

Projection of Technology for Air and Surface Weaponry

Progress in the development of high-density explosives (HEDM), as referred to by the Department of Energy, points to potential revolutionary advances ranging from improved high explosives to many orders of magnitude increase in energy from fission, fusion, and antimatter. Clearly, fission, fusion, and antimatter are not envisaged in the role of tactical warheads. Whether nuclear isomers will be feasible is also debatable However, a continuing problem for explosives is that increasing performance is generally accompanied by increasing sensitivity, often violating Department of the Navy insensitive munition criteria.[10] Meeting these criteria will remain a major concern for air and surface weaponry, as well as undersea weaponry.

Conventional Explosives

The evolution of new explosives for use in metal-driving applications (such as standard missile) has shown significant improvement during the past 20 years. Considering detonation pressure as a figure of merit for explosives used in metal-driving warheads, performance levels for explosives are expected to increase even more significantly in the future. A major breakthrough in explosive chemistry occurred in FY 1987 when the first preparation of hexanitrohexaazaisowurtzitane (CL-20) was achieved in the ONR explosive research program. CL-20 is a new solid explosive compound, chemically related to RDX and HMX, but with considerably higher energy. Calculations of energy in terms of detonation pressure for CL-20 indicate a value of 450 kilobars, as compared with 340 kilobars for RDX and 380 kilobars for HMX. The indicated improvement (70 kilobars above HMX) suggests that a significant improvement in penetration of shaped-charge jets and EFPs can be achieved by replacing HMX with CL-20. CL-20 is made from commercially available chemicals and reagents. A fairly complicated and expensive three-step preparation process was initially used. This has been successfully replaced by a relatively easy method so that CL-20 is now available commercially and thousands of pounds have been made. Formulations based on CL-20 are now being evaluated by all Services for application in high-energy metal driving and in missile propulsion. Beyond CL-20, synthesis efforts in Navy research programs are addressing preparation of materials with detonation pressures in the range of 480 to 500 kilobars. In the far term, superbrisant explosive formulations can be expected which will increase penetration by a factor of two to three.

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[10]Finger, Milton F. 1996. "Energetic Materials, Concepts, Technology," Lawrence Livermore National Laboratory, Livermore, Calif., presentation to the Panel on Weapons, May 13.

New Approaches

Extended Solids

Proven theory at LLNL[11] suggests a promising new class of extended-solid HEDMs. Most conventional chemical energetic materials are molecular liquids or solids, characterized by strong covalent bonds within each molecule and weak van der Waals interactions between different molecules. Though involving similar atomic ingredients, the new phases differ in that they are extended solids, identified by uniform networks of only strong covalent or metallic bonds. Such phases as a class have significantly smaller atomic volumes and correspondingly larger specific energy densities per unit volume. Examples include a polymeric form of nitrogen, an aluminum-like, body-centered tetragonal phase of boron, a distorted tetrahedrally coordinated form of carbon, and the elusive monatomic phase of hydrogen. Figure 2.2 shows relative energetics of HEDM systems. The potential military payoff for polymeric nitrogen would be a signatureless (N_2) gas reaction product in propellants, an explosive with three times the energy of HMX which is approximately equal to liquid H_2O_2. A factor of two or more in energy per unit volume would provide dramatic opportunities for size reduction and performance improvements in precision munitions, e.g., greatly increased mass and velocity of EFPs. A factor of two to three increase in penetration can be expected against hard targets.

Reactive Materials

Thermitic materials are uniquely different from explosives and propellants and fall more into the pyrotechnic class of materials. They are a mixture of solid particulates consisting of oxidizer and fuel. If care is taken to achieve an intimate mixture by significantly reducing the particle size of the reactants, then they will explode violently when shocked. Normally they burn at a relatively low combustion rate.

Thermitic materials are also called high-temperature accelerants (HTAs), self-propagating high-temperature synthesis systems (SHSs) and thermoflux systems. Intermetallics are a special class that involves the reaction of two metals, e.g., boron and titanium. This class of materials produces a very high adiabatic temperature upon reaction. The high temperature can be transported by hot particles or by radiation and, if they contain a polymeric binder, by the gas products of reaction. The high temperatures produced may be useful for neutralizing chemical and biological agents without causing explosive dispersal. They are candidates for destruction of the WMD chemical and biological agents.

[11]Finger, Milton F. 1996. "Energetic Materials, Concepts, Technology," Lawrence Livermore National Laboratory, Livermore, Calif., presentation to the Panel on Weapons, May 13.

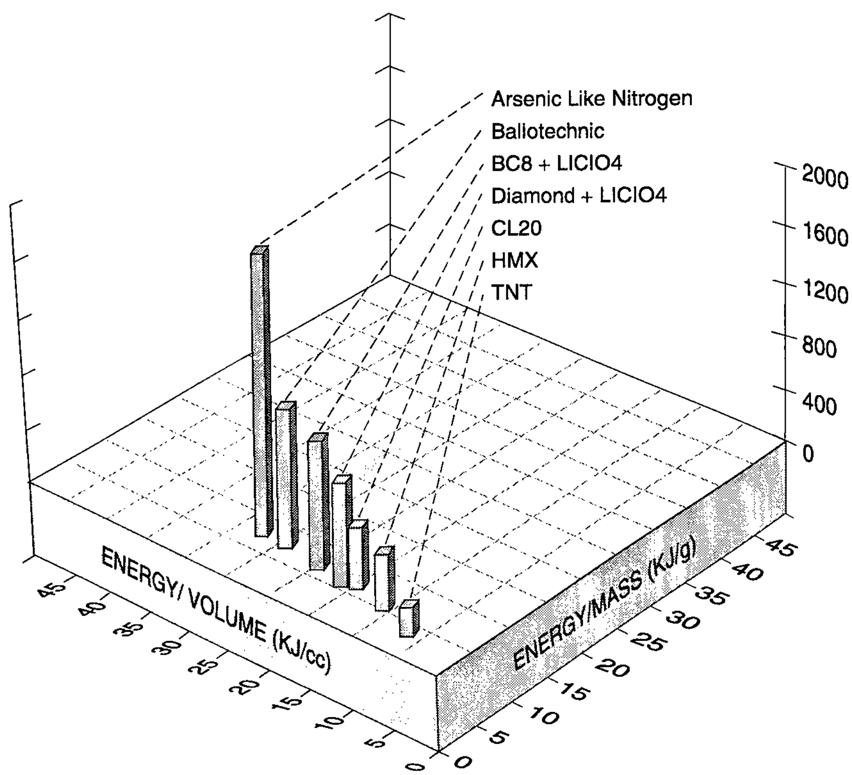

FIGURE 2.2 Relative energetics of high-energy-density materials (HEDM) systems. SOURCE: Milton Finger, Lawrence Livermore National Laboratory, 1996.

Reactive composite materials such as teflon/aluminum, teflon/magnesium, and boron/titanium in projectiles and fragments have been shown to enhance damage to air and surface targets by producing holes three to four times larger than holes produced by a same size inert projectile or fragment. In the near term, the Navy expects to demonstrate a focused reactive fragmenting warhead that will increase target damage threefold and provide a 50 percent increase in lethality against air targets.[12] It is expected that this same technology will be applied to shaped-charge jets and EFPs in the future to significantly increase penetration of armor and increase behind-the-armor damage.

[12]Parsons, M.C. 1995. "Warheads and Explosives Subpanel Overview," OSD Technology Overview briefing to Mr. Richard Menz, Office of the Deputy Director for Research and Engineering, Office of Munitions, Office of the Secretary of Defense, July 10-14.

Nuclear Isomers

Recent evidence of nonfissioning nuclear isomers has spurred LLNL[13] to reexamine isomers as energy-storage materials. Unlike fission and fusion, nuclear isomers could be a clean energy source. The LLNL core program has established the existence of nuclear shape and spin isomers and is focused on determining their fundamental properties. Nuclear isomers offer the possibility of being used as energy storage devices with high energy density, possibly 10^3 to 10^5 times the energy density of conventional explosives. Isomers store energy in metastable states above the stable ground state. Certain nuclei have the ability to absorb energy, then store the energy in the form of increased spin or a distortion of the shape of the nucleus. Energy is released from these nuclei only in the form of gamma rays or electrons ejected from the atom by the emitted gamma ray. Many of the gamma rays found to be emitted from nuclear isomers have energies similar to the energies of inner-shell atomic electrons.

In any of several release mechanisms proposed to date, an isomer source would release energy only after receiving a trigger source of energy. If the trigger causes a slow release of energy, isomers could provide an intense source of heat on demand. This could be utilized to decompose chemical/biological agents. If the trigger produces a more rapid release of energy, there is a possibility that a shock wave can be produced. Currently, it is not known how rapidly the energy can be released. Because the energy release is entirely in the form of gamma rays or electrons, there is no induced radioactivity in surrounding materials and no radioactive byproducts.

Nuclear isomers are at the revolutionary end of the HEDM spectrum. The science is complicated and high risk because of the extreme values involved, but the potential payoff could be enormous. The panel wishes to make clear that it does not hold out much, if any, hope that, within the next 35 years, nuclear isomers will be a practical source of energy for either propulsion or explosives. Many practical problems remain to be resolved. The panel believes that anyone talking about the use of nuclear isomers as a practical source of energy is in the same position as people were in 1936 when they speculated on extracting energy based on nuclear fission or fusion.

Summary

Table 2.1 above summarizes the potential increase in Navy capability relative to undersea, air, and surface weaponry. In general, one can expect the following over the next 35 years:

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[13]McMahan, Andrew K. 1996. "High Energy Density Materials (HEDM) Research at LLNL," Lawrence Livermore National Laboratory, Livermore, Calif., presentation to the Panel on Weapons, May 13.

- A factor-of-two-to-three increase in the penetration of precision miniature munitions deployed from projectiles, aircraft canisters, and the like for wide-area destruction of invading army equipment, such as trucks, tanks, and personnel carriers.
- A factor-of-two-to-three increase in penetration against hard targets such as tanks.
- A significant increase in blast energy (two to three times H_6) by improved explosive formulations resulting in smaller air and surface weapon warheads for the same damage, or a lethal radius increase of 1.4 for the same volume warhead.
- Solid fuel air explosives with blast energy three times that of current fuel/air high-explosive systems (HESs) resulting in increased area coverage and lethality.
- Focused reactive material fragmenting warheads with a threefold increase in damage to air targets.
- Reactive material warheads producing very high temperature particles and/or gases capable of destroying chemical and biological agents in WMD munitions.
- Significant increase in energy from underwater explosives (two to three times that of PBXN-103), resulting in the ability to rupture the hull of all robustly constructed submarines with a warhead equivalent in size to an Mk-46 lightweight torpedo.
- Spinoff of the underwater explosive technology yielding small, highly effective sea mines that are particularly effective in shallow water for controlling the battle space, while minimizing delivery assets.
- New energetic explosives for antitorpedo torpedo (two to three times PBXN-103) that will allow the closest point of approach (CPA) to increase by up to 70 percent, thereby significantly increasing kill probability against high-speed antiship, antisubmarine torpedoes.
- Revolutionary advances in ultrahigh-energy density materials such as nuclear isomers that will offer the potential for destroying bacteriological and chemical warheads and terrorist nuclear devices, and also provide an ultrahigh-energy source for space applications.

Propulsion and Propellant Technology

Background

Since the invention of black powder in Asia over 1,000 years ago and the application of black powder in guns over 700 years ago, weapon designers have sought a greater understanding of the basic chemistry and processing of explosives and propellants to develop more lethal weapons with greater range. In general, an increase in range can be achieved from the development of chemical formulations with a higher-energy density (e.g., specific impulse) or the development of more efficient use of the available energy (e.g., mass fraction). Technol-

ogy to process the materials and store it over long periods of time in a variety of environments is also critical to the production of practical propulsion system.

Today, solid propellant propulsion (guns and rocket motors) dominates all Navy weapons systems from tactical to strategic applications. Other forms of propulsion exist in the inventory (Table 2.3), but this discussion focuses primarily on solid propellant propulsion and is divided into rocket propulsion and gun propulsion.

Rocket Propulsion (Technology Needs)

For the foreseeable future, the U.S. Navy and Marine Corps will be expected to deploy military power in both small regional conflicts (e.g., Bosnia) and large-scale conflicts. The ability of the U.S. naval forces to project a deep strike (e.g., Tomahawk cruise missiles in the Persian Gulf War) and support a Marine Corps expeditionary force in a major amphibious operation remains key to the success of U.S. military forces. The ability to launch missiles at long range from the proposed arsenal ship is crucial to the provision of naval surface fire support (NSFS) for the Marine Corps so that it can implement Operational Maneuver From the Sea (OMFTS).

The proliferation of medium- and long-range tactical ballistic missiles (TBMs) along with inexpensive cruise missiles will probably become commonplace over the next 10 to 20 years. Currently, the Navy's theater air defense programs (upper tier and lower tier) are intended to combat this threat. Future conflicts may require these Navy surface-to-air systems to not only defend against attacks locally but also to provide an umbrella antimissile defense for entire regions. Desert Storm emphasized increased needs associated with distant, time-critical targets such as mobile Scud launchers, hard-target penetration, and weapons that can address a wide spectrum of targets. Key propulsion capabilities for these needs will be to improve delivered specific impulse (I_{SP}) and/or propellant mass fraction (M_f) to increase rocket motor burnout velocity, thereby reducing time to target. Other major considerations include hazards, signature, mechanical behavior and aging, combustion behavior including combustion instability, life-cycle costs, and environmental effects. Divert propulsion technology is also needed to guide the kill vehicle (either kinetic or explosive). Improvements in these key propulsion characteristics are needed for air-to-air, surface-to-surface, and ship-defense missiles to support littoral warfare.

The propulsion industry has always been concerned about hazards associated with their weapons. However, in the last couple of decades this concern has been highlighted by the insensitive munitions efforts of the Department of the Navy. Signature has become an increasing concern because the advantages of stealth aircraft and stealthy missile airframes can be compromised by the detection of visible exhaust signature (both primary and secondary smoke) and infrared or ultraviolet exhaust signatures, and RCS.

TABLE 2.3 Comparison of Propulsion Systems

Propulsion Method	Advantages	Disadvantages	1996 Baseline System, e.g., Guns
Guns	Rate of fire Cost per round	Lower range compared with that of other weapons	5-in./54 naval gun with NACO
Solid-propellant rocket motors	Smallest volume Highest thrust to motor weight Easiest storage and maintainability	Not easily throttleable Cannot be restarted (except pulse motors)	Most common propulsion method for all tactical and strategic missiles: SA-Mk 104/Mk 72 AA-Mk 36/AIM-120 AG-HARM, Hellfire, 2.75-in. rocket SS-VLA/Trident D5
Air-breathing engines	Higher fuel efficiency than solid propellant	Requires booster or aircraft to achieve minimum flight speed	e.g., Tomahawk e.g., Harpoon
Liquid engines	Highest specific impulse Throttleable	Size and weight System weight and size Storage problems (except for some gels)	e.g., no naval weapon systems e.g., almost exclusively limited to space boosters

SOURCE: Jack E. Goeller, Advanced Technology Research Corporation, Burtonsville, Md., and Frank Tse, Naval Surface Warfare Center, Indian Head Division, Indian Head, Md., 1996.

Current Status of Rocket-Propulsion Technology

Since the 1960s, the Navy has employed surface-launched missiles for defense against air attacks. The early propulsion systems for Terrier and Talos employed double-base solid propellants in form of single-stage or two-stage (boost-sustain) rocket motors. The evolution of increase in specific impulse of double-base solid and composite propellants is shown in Table 2.4.

Aircraft from the former Soviet Union were the threat that these early systems were intended to counter. The missile systems permitted intercepts at far longer ranges than the antiaircraft guns systems, and ships carrying these missiles are easily distinguished from the newer systems by either a single or double launcher. These earlier missile systems were subsequently replaced in the 1970s with the Standard Missile system combined with Aegis radar systems. Propulsion for the Standard Missile family generally employs PBHT/AP/Al solid propellants with the highest delivered impulse available in the 1970s or 1980s (240 to 250 seconds). The Standard Missile system represents a first-generation antimissile system; however, the propulsion systems offer only a modest increase in range. The current baseline for the surface-to-air propulsion is the Block IV system employing a Mk-72 booster with thrust-vector control mated with the Mk-104 dual-thrust rocket motor (DTRM). Basically, all current U.S. Navy ships employ the vertical launch system. The Navy is also exploring the possibility of deploying the Army's Advanced Tactical Missile System (ATACMS) for NSFS. Table 2.5 lists the characteristics of other naval weapon systems employed by the fleet.

In the two decades following World War II, rapid advances in performance were achieved by changing from double-based propellants to propellants based on ammonium perchlorate/rubbery binder/aluminum fuel. This performance is largely the result of the reaction of AP and aluminum with the production of aluminum oxide and HCl in the exhaust. The aluminum oxide provides a highly visible incandescent plume that can be seen for miles and a primary smoke trail resulting from the condensed aluminum oxide. The HCl and water in the exhaust, under certain conditions of temperature and humidity, can produce a secondary smoke contrail. Attempts to find minimum signature replacement propellants have resulted in a loss of performance. Performance is improved with minimum signature propellants using HMX or RDX as the major ingredient. Unfortunately these propellants are hazard class 1.1 (mass detonable). In an attempt to make minimum signature propellants that would be hazard class 1.3 (mass fire), performance degraded.

Recently the Navy succeeded in making hazard class 1.3 minimum-signature propellants meeting the future minimum smoke requirements using the new ingredient CL-20.

Advances are being made in several other areas: new energetic materials such as CL-20, ADN, difluoramines, hydrazinium nitroformate (HNF), new en-

TABLE 2.4 Tactical Rocket Motor Technology Evolution

	1950s	1960s	1970s	1980s
Double Base				
Propellant				
I_{SP}	190 to 230 s	200 to 230 s	210 to 230 s	240 to 250 s
Composition	NC-NG	NC-NG, ADD'VES	CMDB	HMX-RDX/NC-NG-BTTN
Case				
Material	Steel	Al or steel	Steel	Steel
PV/W		2,500 to 3,000 psi burst	2,500 to 3,000 psi burst	
Insulator/liner material	Polyurethane	Asbestos	Rubber/asbestos or	
	Asbestos	Phenolic	Graphite phenolic	Si-filled neoprene
Nozzle				
Throat material	Carbon	Graphite	Glass	Graphite phenolic
Exit cone	Phenolic steel	Phenolic steel	Phenolic steel	Resin phenolic
Composite				
Propellant				
I_{SP}	200 to 260 s	210 to 260 s	230 to 260 s	250 to 255 s
Composition	AP/PU, PS, Other/Al	AP/CTPB/Al	AP/HTPB/Al	AP/PBHT/ZrC
Case				
Material	Steel	Al or steel	Steel	Steel
PV/W		100 to 200,000 psi	2,500 to 3,000 psi burst	150,000 psi
Insulator/liner material	Polyurethane	Rubber	Rubber, asbestos, or EPDM	EPDM, asbestos, or Kevlar
	Asbestos	Asbestos		
Nozzle				
Throat material	Graphite steel	PG, ATJ graphite	PG graphite steel	Pyrolytic graphite phenolic
Exit cone		Si/phenolic		

SOURCE: Hoffman, Harry. 1988. "CPIA Propulsion Technology Briefing," Chemical Propulsion Information Agency, Columbia, Md.

TABLE 2.5 1996 Baseline Rocket Propulsion Summary

Missile Designation		Length (ft)	Diameter (in.)	Weight (lb)	Rocket Motor Designation		
Air-to-Air Missiles							
Sparrow	AIM 7	12	8	510	Mk 58		
Phoenix	AIM 54	13	15	989	Mk 47		
Sidewinder	AIM 9	9.4	5	188	Mk 36	MOD 11	
AMRAAM	AIM 120	11.8	7	300			
Cruise Missiles							
Tomahawk		18.3	20.4		Mk 106		Booster
Tomahawk		18.3	21.4		Mk 111		Booster
Harpoon		15	13.5		Mk 96		Booster
Surface-to-Air Missiles							
SM-1 MR		14.6	13.5	1,380	Mk 56		DTRM
SM-2 MR		14.6	13.5	1,380	Mk 104	MOD 1 and 2	DTRM
SM-2 ER		26.2	13.5	2,980	Mk 72		Booster
SM-2 ER					Mk 104	MOD 3	Sustainer
Fleet Ballistic Missiles							
Trident C-4		34	74	73,000			Multistage
Trident D-5		44	83	126,000			Multistage
Air-to-Ground Missiles							
HARM	AGM 88	13.6	10	80			
Strike	AGM 45	10	8	18			
Maverick	AGM 65	8.2	12	12			

SOURCE: Frank Tse, Naval Surface Warfare Center, Indian Head Division, Indian Head, Md., 1996.

ergetic polymers and plasticizers, nanoparticle metals; energy management devices such as thrust vector control (TVC), integrated acro-TVC, pulse motors, throttleable motors, pintle nozzles; enabling technologies such as composite cases that allow for higher operating chamber pressures; and air-breathing propulsion where the oxidizer (oxygen) is derived from the air and are not carried on board as the solid propellant.

Projections for Rocket-propulsion Technology

The core of the propulsion technology research will be driven by the DOD's Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program. This program involves the basic research in rocket propulsion for all three U.S. military Services and the National Aeronautics and Space Administration (NASA).

TABLE 2.6 Goals of Tactical-Missile Propulsion Systems

		I_{SP} (sec)[a]	Mass Fraction[b]
1995	State of the art	233/239/247	0.60 to 0.80
2000	3 percent increase in delivered energy	240/246/254	+10 percent
2005	7 percent increase in delivered energy	249/256/264	+20 percent
2010	15 percent increase in delivered energy	268/275/284	+30 percent

[a]The first number under specific impulse applies to minimum signature, the second to reduced smoke, and the last number to smoky exhaust.

[b]Mass fraction is defined as the mass of the propellant divided by the total rocket motor mass.

SOURCE: Compilation of data from (1) "Baselines for the IHPRPT Initiative (1993 SOTA)," *Integrated High Payoff Rocket Propulsion Technology,* Department of Defense, Washington, D.C., 1994, and (2) Jones, Anita K., 1994, *Defense Technology Plan,* Office of Defense Research and Engineering, Department of Defense, Washington, D.C., September.

A particular emphasis is being placed on environmentally friendly propellants (for example, reduced ammonium perchlorate) and appears to be heavily focused on large space-booster development. The IHPRPT program was initiated by DOD in 1994 to achieve the goals listed in Table 2.6 with reference to the current state of the art for tactical-missile (TM) propulsion systems.

Figure 2.3 shows how the specific impulse has increased over the years for solid-propellant tactical rocket motors. Figure 2.4 shows the corresponding increase in mass fraction. The subsequent increase in specific impulse has at best been modest. The goals of the IHPRPT program are shown for comparison. Recognizing that the tactical propellant technology now has well-defined goals with specific impulse of smoky propellants increasing to about 285 seconds by the year 2010, it appears reasonable that the specific impulse will increase to about 300 to 310 seconds by the years 2020 to 2030. Some of the enabling technologies that should be pursued are discussed below.

The Navy Department is conducting research in novel high-density crystalline solids and polymers to maximize energy density in solid-propellant and explosive formulations with usable hazards classification. The near-term goal is to achieve the IHPRPT goal of 15 percent improvement in specific impulse by 2010. Several new ingredients have been recently synthesized/evaluated and may find application in this time frame. These new ingredients include ADN, CL-20, HNF, nanoparticle aluminum, dimethylbitetrazole (DMBT), and bismuth trioxide (Bi_2O_3).

As in explosives research, ADN and nanoparticle metals are being considered for propellants.[14] ADN was first synthesized by the Russians in the 1970s and subsequently at Stanford Research Institute without knowledge of the Rus-

[14]Miller, Richard S. 1996. "Energetic Materials, Concepts, Technology," Office of Naval Research, Arlington, Va., presentation to the Panel on Weapons, May 13.

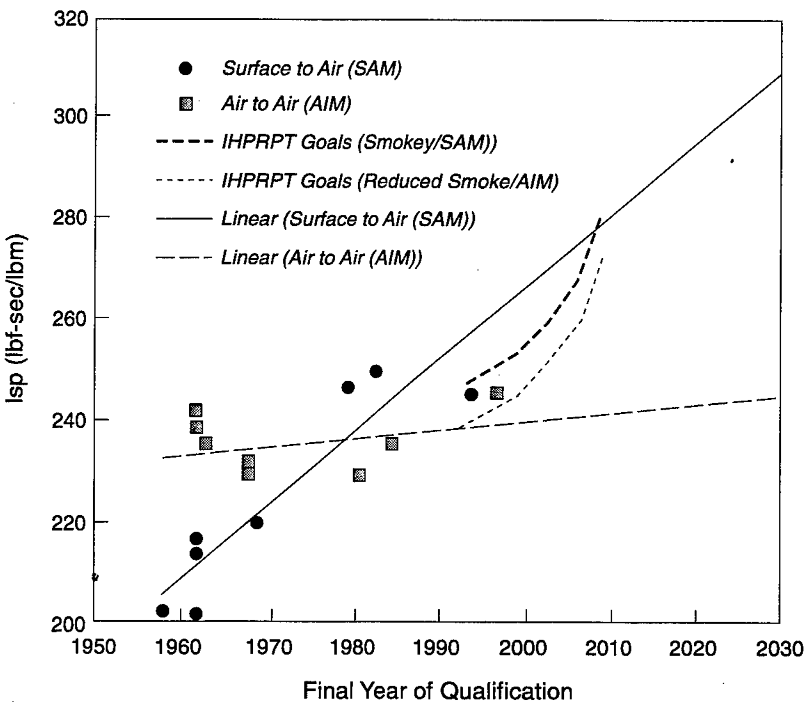

FIGURE 2.3 Historical increase in delivered specific impulse for solid propellant tactical rocket motors. SOURCE: Jack E. Goeller, Advanced Technology Research Corporation, Burtonsville, Md., and Frank Tse, Naval Surface Warfare Center, Indian Head Division, Indian Head, Md., 1996.

sian work. It is a strong oxidizer and shows promise for both metallized and unmetallized propellants. One of its strong advantages is that high performance can be theoretically achieved at relatively low solids loading. It also does not contain chlorine and does not produce HCl in the exhaust. A metallized propellant based on this ingredient optimizes to 271.8 seconds specific impulse at standard conditions but has a modest density-impulse of 18.1 because of the low density of ADN. Calculations for a minimum signature propellant show several advantages including standard specific impulse to slightly over 259 seconds and density specific impulse to 15.7 over a fairly wide range of propellant compositions (an advantage for tailoring the propellant formulation without losing performance). It also has a high burning rate. Its disadvantages include relatively low melting point, hygroscopicity, low density, sensitivity to some wavelengths of light, need for a stabilizer, and at present low-volume production and high cost. The hazard sensitivity of propellants based on ADN needs to be determined.

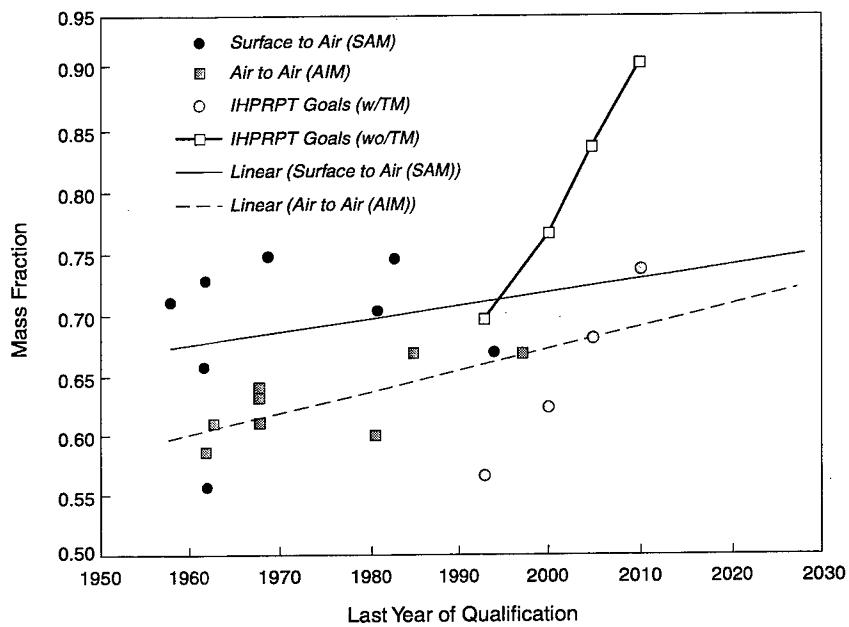

FIGURE 2.4 Historical increase in mass fraction for solid propellant tactical rocket motors. SOURCE: Jack E. Goeller, Advanced Technology Research Corporation, Burtonsville, Md., and Frank Tse, Naval Surface Warfare Center, Indian Head Division, Indian Head, Md., 1996.

Propellants incorporating nanoparticle aluminum have shown increased burn rates (doubling) and increased combustion efficiency that will translate into increased delivered I_{SP}.

CL-20, which was first synthesized in 1987, can be used in both hazard class 1.1 and 1.3 propellants.[15] In the hazard class 1.1 metallized propellant, it can increase the specific impulse to 272 seconds. Based on current tests, its most probable application will be in a minimum signature, hazard class 1.3 propellant. CL-20 with ammonium nitrate and energetic binder has specific impulse over 243 seconds at standard conditions and over 271 seconds at 6,000 psi chamber pressure. This propellant has been successfully demonstrated in Hellfire hardware and showed a steady burn, high performance, and minimum signature. Since CL-20 is a relatively new ingredient, it is available in limited quantities (1,000-lb batch sizes) and is relatively costly at this point. Since CL-20 is also being considered in explosive and gun-propellant applications, the demand for

[15]Boggs, T. 1997. "Propulsion Science and Technology for Naval Weaponry," NAVAIRWARCEN/WPN/DIV memorandum of February 17.

this ingredient and production rates will increase. As production rates increase, the costs will decrease. Work needs to be performed to determine the high-pressure combustion behavior (including stability), the mechanical behavior, and aging of these propellants.

Fluorine and oxygen-rich energetic crystals and polymers will provide a new approach to increasing the specific impulse of composite propellants, explosive energy density, and energy release rates. Currently targeted high-density molecular solids include difluoraminated analog of HMX (HNFX). New molecule basic research is focused on realizing the high-performance potential of difluoramine-based compounds and high-nitrogen compounds. An intense effort is under way to develop these novel and promising analogs to nitrainine and nitrate ester oxidizers. In the pursuit of decoupling performance and sensitivity, new classes of high-nitrogen compounds with high-calculated energies, but with structural features that are designed to decrease sensitivity, are under development.

The high-nitrogen compounds of interest show increased density and heat of formation over HMX and CL-20 and have excellent oxidizing power. Possible candidates are included in Table 2.7. These proposed compounds are considered chemically plausible by synthetic organic chemists at LLNL, and some progress toward their eventual synthesis has been achieved, Although there is still considerable risk, there appears to be a potential high payoff in the time frame of the study.

Theoretical performance estimates using the above parameters for both metallized and minimum signature propellants are shown in Table 2.8. These estimates are all for the standard case of 1,000 psi chamber pressure venting to one atmosphere. Increased specific impulse could be achieved by higher operating pressures. Many of these prospective propellants have extremely high chamber temperatures and could present design problems.

The U.S. Air Force Phillips Laboratory[16,17] is developing an innovative class of solid propellants including hydroxylammonium nitroformate (HANF) and hydroxylammonium dinitramide (HADN) oxidizers. The HADN-based propellants have high strength, have inherently high burn rates, and are projected to exceed the IHPRPT goal for the year 2005. For example, a HANF-based propellant is projected to have a specific impulse of 272 seconds. Similarly, a HADN-based propellant is projected to have a specific impulse of 273 seconds. Research is also being conducted on advanced tactical propellants including minimum and smoky propellants to meet the IHPPPT 2010 goals.[18] Oxidizers include triazido carbonium dinitramide (TAZDN), HADN, and oxidizers proprietary to Alliant

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[16]Wucherer, E.J. 1996. "Advanced Propellant Ingredients," briefing by USAF Phillips Laboratory to the USAF Scientific Advisory Board (SAB), February 1.

[17]Hawkins, T.W. 1996. "Advanced Propellants," briefing by USAF Phillips Laboratory to the USAF Scientific Advisory Board (SAB), March 27.

[18]Carrick, Patrick G. 1996. "HEDM (High Energy Density Matter) for Rocket Propulsion," briefing by USAF Phillips Laboratory to the USAF Scientific Advisory Board (SAB), January 30.

TABLE 2.7 High-Nitrogen Compounds

Compound	Empirical Formula	Density (g/cc)	Heat of Formation (kcal/mol)
Tetranitro-bi-pyrazole	$C_4N_8O_8$	2.15	119
Dinitro-bi-triazole	$C_2N_8O_4$	2.24	173.07
Mono-nitro-di-N-oxide-triazole-tetrazole	$C_2N_8O_4$	2.25	206.12

SOURCE: Data from Lawrence E. Fried, Lawrence Livermore National Laboratory, Livermore, Calif., 1996.

TABLE 2.8 Theoretical Performance

	Metallized		Minimum Signature	
	Standard I_{SP}	Density Impulse	Standard I_{SP}	Density Impulse
Tetranitro-bi-pyrazole	272.6	19.82	269.4	18.77
Dinitro-bi-triazole	283.1	21.34	279.6	20.0
Mono-nitro-di-N-oxide-triazole-tetrazole	289.1	21.83	286.7	20.6

SOURCE; Data from Thom Boggs, Naval Air Warfare Center, Weapons Division, China Lake, Calif., 1996.

and Thiokol. Some of the binders and fuels include cubane, aluminum hydride (AlH_3) and glycidylazide polymer (GAP). A smoky solid propellant of TAZDN/GAP/Al is estimated to have a theoretical specific impulse of about 292 seconds. A smoky hybrid propellant of HADN/Cubane/AlH_3 is estimated to have a theoretical specific impulse of 296 seconds. A minimum signature hybrid of HADN/Cubane/polybuta-diene (PBD) is estimated to have a theoretical specific impulse of about 278 seconds.

The Phillips Laboratory is also performing research in HEDM. The objective is to develop and exploit high-energy atomic and molecular systems as energy sources for rocket propulsion. Cryogenic solids[19] including solid hydrogen, solid oxygen, and solid hydrocarbons are being investigated with high payoff expected for Air Force launch vehicles. Potential increase in specific impulse to 390 seconds using revolutionary cryo technology of LOX/LH2 is being projected. Design of these propulsion systems will be somewhat more complicated and perhaps best suited for launch vehicles rather than volume limited tactical missiles.

[19]Penn, D., and R. Drake. 1996. "Evolved Expendable Launch Vehicle Support," briefing by USAF Phillips Laboratory to the USAF Scientific Advisory Board (SAB), February 1.

The Air Force is also pursuing advanced concepts that have theoretical specific impulse of 600 seconds for extended solids (N_8) using high pressure, 1,200 seconds for metallic hydrogen and even higher for antimatter.

Summary (Rocket Propulsion)

Certainly, the focus of most S&T propulsion programs is on the development of new and more energetic propellant formulations. At times, it is difficult to distinguish between explosive and propellant research efforts. New propellants based on new ingredients promise increased performance for future missile systems, especially if these propellants can be burned at higher pressures. These gains stem for increases in specified impulse and increased density.

Propulsion technology advancements in the last 20 years have been relatively modest, and for this reason the IHPRPT program was initiated to accelerate progress. Given that propellant research being pursued by the military services and NASA has a reasonably high probability of achieving the IHPRPT specific impulse goal of about 285 seconds by the year 2010, it appears reasonable to project a fielded specific impulse of about 300 to 310 seconds by the years 2020 to 2030. The key to the success will be finding a superior replacement for the aluminum AP oxidizer combination that has been the backbone of composite propellants for 40 years.

Improvements in mass fraction are also likely. However, the IHPRPT goals are above the historical trend line (see Figure 2.4). To achieve the IHPRPT goals, metallic materials now used in most rocket motor cases will have to be changed to high-strength and low-density composite materials. These new materials will allow higher chamber pressure and lower system weight.

Assuming the IHPRPT goals of 285-second impulse and 30 percent improvement in mass fraction are met by the year 2010, significant improvements can be expected in rocket propulsion systems fielded in the 2010 to 2020 time frame. IHPRPT makes the following projections:

- Increased range by 50 percent thereby increasing safe standoff and expanding battle space coverage.
- Increased missile speed by 20 percent resulting in less time to target, greater energy for maneuvering, and increased opportunity for engagement of threat missiles.
- Increased missile payload (relative to current systems) by 100 percent resulting in larger warhead for increased lethality.
- Decreased propulsion size and weight (relative to current systems) by 25 percent resulting in increased firepower.

If a specific impulse of 300 to 310 seconds can be achieved by 2020, the range of fielded systems in the 2020 to 2030 time frame should increase by close to 70 percent.

Gun Propellants

Background

The history of gun-propellant technology is quite long and rich, but relatively few advancements have been made over the last 40 years. Perhaps the most significant advancement in propellant technology occurred from approximately 1840 to 1890 when chemical experiments by Schoenbein in Germany, Abel in England, and Nobel in Sweden led to the development of nitrocellulose. Nitrocellulose produced a highly energetic and stable gun propellant compared with black powder. This discovery became the basis for double-base propellant used in rockets and guns up to and including the present day. This evolution of nitrocellulose-based propellants includes the Navy's current baseline gun system (5-in./54 caliber) using Navy cool (NACO) propellant.

Gun-propellant Technology Goals

The primary goals of gun-propellant technology development have been to increase muzzle energy, decrease barrel wear, and, to a lesser degree, decrease the sensitivity and environmental impact of the gun propellant at any point in its service life. Increasing muzzle energy is generally achieved by utilizing more energetic ingredients or increasing energy density of a charge through use of multiple propellants in a single grain (e.g., U.S. Army Fastcore program) or compressing the propellant grains to achieve a higher density of grains per charge. Electrothermal-chemical (ETC) technology increases ballistic efficiency by directing a powerful electrically formed plasma that reacts with propellants configured with a conventional cartridge. The approach provides a major interior ballistics advantage because of its ability to regulate combustion rate and pressure through precise control of electrical pulses. ETC gun technology has been proposed as a futuristic system for NSFS and cruise missile defense.

The development of current nitramine-based propellant (e.g., RDX or HMX) for gun-propellant formulations in production today are intended to provide higher muzzle velocity and correspondingly higher range than the earlier nitrocellulose or double-base gun-propellant systems. Generally barrel life is increased by lowering flame temperatures or by the addition of chemical additives. Finally, decreasing the sensitivity of all energetic materials to hazards such as bullet impact or fire has been extensively researched since the 1980s. Certainly, the development of the low-vulnerability ammunition (LOVA) at the Naval Surface Warfare Center, Indian Head Division (NSWC/IHD) for the U.S. Army M-1 tank is the most well-known example of a high-performance gun propellant combined with lower sensitivity to hazards.

TABLE 2.9 Energy Per Gun Firing

1930	1950	2000	2030
Pyro (single base) 7 megajoules/shot	NACO 11 megajoules/shot	Nitramine 18 megajoules/shot	24 megajoules/shot

Current Status of Gun-propellant Technology

No new gun propellants have been introduced into the naval forces' inventory for the last 20 years. Only one new Army propellant (M-43 LOVA) has been placed in the inventory (2 million pounds), and it entered service over 10 years ago. The M-43 propellant was an outgrowth of a joint Army-Navy 6.2 program in the 1970s. The primary gun development effort today is the Navy's NSFS program utilizing the ERGM. The goal of this system is to extend the range of the 5-in./54 gun from 13 miles to 63 miles by utilizing a more energetic gun propellant combined with a rocket motor mated to the projectile. The current plan for ERGM is a nitramine-base gun-propellant formulation similar to the Army's M-43 LOVA.

Projections for Gun-propellant Technology

From a naval gun-propulsion technology perspective, a relatively modest improvement in energy output can be expected in the next 30 years. Table 2.9 lists the energy output of the primary gun propellant used in the last 60 years.

Air-breathing Missile Propulsion

Background and Status

Although the application of ramjets for missile propulsion has been limited, significant progress has been made since the Germans' application of the pulsejet in the World War II Battle of Britain (V-1 missiles). This progress has involved the development and test demonstrations of liquid-fuel ramjets for surface- and air-launched antiair and surface missiles, solid-fuel ramjets for air-launched antiair and surface missiles, and air-augmented/ducted solid rockets for surface- and air-launched antiair missiles. Of these, only the liquid-fuel ramjet has been selected for application in the Navy's Talos and the Air Force's BOMARC missiles that were operational in the mid-1950s to 1980. When the Talos was removed from the fleet in 1980, the remaining missiles were modified to become the Vandal supersonic target, which is the only U.S. ramjet operational at this time.

Ramjet vehicle speeds have progressed from subsonic to supersonic cruise speeds of Mach 2+ at low altitude and Mach 3+ at high altitude. During this period, the rocket boosters required for propelling the ramjet vehicles up to ramjet take-over speed have progressed from separate tandem designs to designs integral to the ramjet combustor. Liquid fuels have advanced from the initial propylene oxide and kerosene to JP-10, which is the current fuel; with this progression, the volumetrical heat of combustion of the fuels has increased by almost 18 percent. Slurry fuels containing powdered metals for increased volumetric heating values have also been investigated, but the expected higher performance has not been obtained because of lower combustion efficiencies and fuel control problems resulting from high fuel viscosities at low temperatures. Solid ramjet fuels have progressed from compressed, readily combustible metal powders (such as aluminum or magnesium) to polymeric organic fuels (polymer beads in hydroxy-tenninated polybutadiene binder) to metal powders in the polybutadene binder. However, the solid-fuel ramjet demonstrations used the polymeric organic fuels without metals because of their favorable regression rates and good combustion efficiencies.

Currently, the only ongoing conventional ramjet effort is the Department of the Navy's low-drag ramjet (LDRJ), which is a high-performance liquid-fuel engine that has no external control surfaces and thus provides a low-drag airframe. Attitude control of the airframe is accomplished by thrust vectoring the aft portion of the ramjet combustor with its associated nozzle.

Feasibility of an air-augmented/ducted rocket propulsion system has been demonstrated by connected pipe combustor tests. There is an ongoing effort to demonstrate a throttleable system (variable flow ducted rocket) by semi-free-jet tests.

Military interest in the supersonic combustion ramjet (scramjet) concept began in the late 1950s and culminated in the first free-jet (M5-7) demonstration of a scramjet engine providing positive thrust. The fuels used in the test were a borane or mixtures of borane with hydrocarbons. Further investigations led to the development of a dual-combustion scramjet combustor concept that uses a hydrocarbon fuel, thus resolving the pyrophoric and toxic problem with the borane fuel. Component developments for a scramjet engine demonstration are under way.

Ramjet and air-augmented/ducted-rocket propulsion theoretically demonstrate their superiority in long-range missions requiring limited time to target. Also, their sustained cruise speed provides an aerodynamic heating environment that is significantly lower than that encountered with a comparable performance solid rocket and thus more compatible with heat-sensitive missile components such as electronic packages and seeker domes.

Scramjets as an alternative hypersonic propulsion mode offer some political as well as operational advantages. Although rocket-propelled ballistic missiles may probably be a better option for achieving short flight times for land attacks, especially if schemes proposed for producing much cheaper precision-guided ballistic rockets are realized (see Chapter 3), they are currently limited by treaty

to ranges of 600 km when launched from ships. Unless the treaty constraints are relaxed, the scramjet would be the only means to strike land targets quickly from ships at longer ranges, should this prove necessary or desirable in the future. This capability was considered by some to be especially important when the fleet was threatened with Soviet land-based bombers that were able to maneuver at low altitude behind a jamming screen over the horizon from the battle group. Although this problem has obviously diminished with the demise of the Soviet Union, there is no guarantee that over the next 25 to 35 years a similarly stressing air threat may not reappear.

Historically the downsides to scramjet missiles have been high cost, guidance difficulties, and reduced payloads. The real scramjet potential for very high speeds will probably continue to be stymied for many years by the cost of materials required to overcome the heating problems created by high sustained speeds. Today's material technology makes speeds over Mach 6 or 7 unaffordable, and as noted earlier, promising, more affordable materials have yet to be demonstrated. Also, the hypersonic-speed stress-guidance technology, e.g., radar-seeker design, is complicated by the plasma buildup around the front of the missile, and IR seekers have limited utility in the intense self-generated infrared background. On the other hand, the smaller payload as the price for the greater missile speed and/or range would not appear to be a problem for air targets and should not be for surface targets if GPS/Inertial Navigation System (INS) guidance is employed to achieve high-impact accuracies against at least fixed targets.

Projections for Air-breathing Missile-propulsion Technology

Performance improvement of liquid-fuel ramjets will continue through improved combustion efficiencies (> 90 percent) and formulation of liquid fuels having higher volumetric heats of combustion (increase of 10 percent). Also, improved thrust-to-weight ratios will be obtained by application of structural plastic/composite materials. The complexity of the design of liquid-fuel ramjet engine components will be reduced to provide a decrease in ramjet costs and to improve reliability. Solid-fuel ramjet performance will be improved through increases in combustion efficiencies and regression rates of metallized fuels brought about by the application of combustion additives and combustor design improvements.

The feasibility of a throttleable (4:1) air-augmented/ducted rocket will be demonstrated by semi-free-jet tests, and further refinements will increase the throttleability by at least 50 percent. A flight-weight scramjet engine having a performance of Mach 4-8 will be demonstrated by ground tests. This demonstration will occur only after a substantial effort is conducted to identify or develop materials that are survivable in the engine's harsh, high-temperature environment and the development of application designs for the materials.

WEAPON SENSORS AND TERMINAL GUIDANCE

Background

Weapons that can hit targets with high reliability greatly alter the equations of combat—a fact demonstrated first in Vietnam, and later, impressively, during Operation Desert Storm. The pace of battle, the supporting logistics required, the variety of targets that can be engaged, the number of sorties needed, and the losses associated with those sorties all experience dramatic improvement when precision munitions are introduced. Following are the elements of precision in munitions:

- Sensors that can detect, identify, and locate targets with precision.
- Sensors that can guide a weapon to the target.
- Kinematic and control flexibility adequate to respond to the sensor-derived information and get the weapon on target.

This section addresses the first two of these three elements—the weapon-guidance sensors.

Weapons may be guided to targets either through GPS/INS navigation or through sensors that detect and recognize the target and provide appropriate guidance direction. GPS/INS works well against stationary targets whose coordinates are precisely known. Sensors and terminal guidance are needed for precision attack in cases where the target is moving, where the target coordinates are only approximately known, or in search-and-destroy operations such as aircraft and helicopters often perform. Even against stationary targets, where very accurate attack is needed, as in attacking a room in a building or a critical structural member of a bridge, sensor-based terminal guidance is required.

In current practice, the sensors on weapons have the narrow task of finding an identified and assigned target or target feature in a relatively narrow field of view and providing the guidance data necessary for the control system to bring the weapon onto the aim point. This can be accomplished with great accuracy; specific features on the target can be attacked with accuracies measured in inches to feet in many cases. The sensor might be a laser spot detector, a visible or IR-imaging system, a three-dimensional laser mapper, an active or semiactive radar, a passive radar receiver, or an acoustic direction finder.

Mobile autonomous weapons—weapons that search out targets and attack them—have entered the scene in a limited way. Smart submunitions such as sensor-fused weapons (SFWs), BAT, and search-and-destroy armor munition (SADARM) locate and attack vehicles within a restricted footprint. Nonmobile autonomous weapons are employed in the form of mines and booby traps. Full autonomy, the ability to cruise over large areas to find and attack a variety of targets, is not yet feasible. The cost and capabilities of ATR do not yet support such weapons generally, and there is a reluctance to trust automated systems with

life-and-death decisions. Simple, single-function versions, such as loitering antiradiation weapons (like the canceled TACIT RAINBOW program) may appear soon. Although disappointments have been experienced thus far with ATR, future computing capabilities may make adequate ATR achievable.

The full impact of imaging sensors with precision guidance has yet to be realized and may be more far-reaching than commonly imagined. It is useful to consider the minimum amount of energetic material required to disable a fighting vehicle or an artillery piece. If the energetic material can be precisely placed on some critical component of the target, the answer is probably a small fraction of a kilogram, e.g., the disabling effect of a shaped charge penetrating a gun barrel, a traversing mechanism, or a drive sprocket would put the vehicle out of action until it could undergo depot level repair. Heretofore the U.S. attack paradigm has been to achieve just sufficient precision to hit a vehicle, and weapons have been sized to be massively lethal with a hit anywhere on the target; with imaging sensors, there is no reason not to set our sights on hitting a selected aim point within the target with an accuracy of several to 10 centimeters. This level of precision attack opens the door to new types of strike weapons—very small and very smart. Additionally, such weapons would produce very few human casualties—a consideration already coming to prominence. The Defense Advanced Research Projects Agency (DARPA) program in microflyer development (very small UAVs) might provide a novel class of delivery vehicles for such *scalpel* weapons. This technology could lead to "hit-iles" instead of "miss-iles."

Major advances are being made across a broad front in military sensor technologies. R&D funding by the three Services, and DARPA is addressing the critical factors of size and weight, cost, and performance. Radar, millimeter-wave (MMW), visible and infrared, laser, image-processing, and inertial-navigation sensor technologies are being pursued, and the improved technologies are being applied to weapon systems. As a consequence, precision-weapon delivery, which heretofore has been cost-constrained to employment against high-value targets, will be technically feasible and affordable over a much expanded range of weapons, targets, and engagement scenarios. Within 20 years, those advances which are being worked today should be fully realized and widely deployed, even given the setbacks and defeats that often attend ambitious development programs. Within the 25- to 35-year span of interest to this study, the capabilities of familiar sensors should be dramatically advanced beyond even the ambitious goals of the current R&D activity, and novel sensors that are not presently envisioned may enter the scene.

Sensor Technologies

The following sections are brief descriptions of some of the potentially important developments under way currently.

Semiactive Guidance

For projectiles, bombs, and missiles, semiactive guidance is a well-established capability, widely deployed with air-attack weapons, artillery, ground-launched antiarmor weapons, and air-to-air and surface-to-air missiles. Radar semiactive guidance is widely employed in antiaircraft missiles, and lasers and MMWs are employed in all these roles. Both spot-homing and beam-rider designs are in use. The current development thrust sees laser and MMW technologies being applied to smaller weapons, bringing the advantages of precision delivery into combat roles where, previously, saturation firepower was required to achieve useful results. Potential developments include 60-mm projectiles, using W-band semiactive guidance, for short-range antiship missile defense (ASMD) (CIWS replacement, but with significantly greater range than the current CIWS), and 2.75-in. rockets using laser semiactive or scatter sensor beam-rider guidance.

It is reasonable to speculate on how far down in size semiactive laser guidance will be applied in the future. Forty millimeters (40 mm) seems to be a straightforward, if nontrivial extrapolation. Extending all the way down to small arms (currently 7.62 mm and 5.56 mm) does not appear to be out of the question as far as laser sensors are concerned, and at that level the major issue will be the feasibility of controls for maneuver. It will be difficult to meet the control and accuracy requirements with spin-stabilized high-velocity projectiles, but possibly a comparably effective small caliber (< 10 mm), modest speed (~400 m/s), fin-stabilized rocket with an explosive tip could be developed using MEMS technology. This would extend the benefits of precision munitions down to the individual soldier or marine.

The charm of semiactive guidance is that the disposable sensor and processor on the weapon are simple and inexpensive. The expensive components are located on the designation platform and are conserved. However, target designation for semiactive guidance, particularly against ground targets, can be a risky enterprise. Targets equipped with threat-warning receivers can riposte with shootback against the designator platform. Additionally, counterdesignation, antisensor weapons, or rapidly deployed obscurants may be employed to defeat the functioning of the homing sensor. Tactics (late designation) and technology (coded designators, minimal exposure of the designator platform) have been developed to preserve the utility of semiactive guidance in the face of these responses, but nevertheless the designating platform must stay within line of sight to the target until the weapon has arrived. Launch-and-leave capability is preferable operationally, but in that architecture the throwaway sensor and processor are more expensive.

High-density IR Focal-plane Arrays

Partly as a result of improved yield in manufacturing and the growth of a commercial market, these arrays are becoming affordable. Thermal imaging

systems are being added to missiles and to small weapons, such as rifles and Stinger launchers, where they were previously impractical for reasons of size and cost. Additionally, advances in uncooled IR focal planes will support the proliferation of very cheap, modest-performance thermal imagers at all combat levels.

Imaging sensors on weapons can be employed in three distinct architectures:

1. *Lock-on-before-launch.* Targets are acquired by the launch platform, the weapon's imaging sensor is locked on to the target before launch, the weapon is released from the platform, and image processing on board the weapon preserves the tracking lock on the target to provide guidance data. This mode requires that the launch platform come to within a clear line of sight of the target, a risky proposition when there is low cloud cover and the launch platform must come within range of ground fire and air-defense artillery. However, it need not linger in hazardous territory any longer than it takes to acquire the target and launch the weapon. Standoff range is limited to the distance at which resolution of the sensors on the weapon and the launch platform permit target acquisition and identification. This is employed on weapons such as IIR Maverick and AIM-9X. Visible imager versions (using video imagers) were developed and employed prior to the IR versions.

2. *Operator lock-on-after-launch.* The weapon is launched into a basket, and the weapon sensor transmits the scene ahead to the operator on the launch platform (or another platform), who sets a track gate on the target when the weapon has approached within clear line-of-sight and recognition range. This permits long standoff range but requires data and command communication links between the weapon and the platform. This is very effective but has been relatively expensive and has some susceptibility to data-link jamming. To date, the relatively poor resolution of the imaging IR sensors, combined with the slow response of human operators, has limited the speed of the weapon. IR imagers will get much better in the future, but people probably will not and man-in-the-loop considerations will probably continue to limit such weapons to subsonic approach to target. If the weapon has any significant flight and maneuver capabilities, the launch basket can be quite large. Remotely piloted weapons that cruise out in search of as-yet-unacquired targets are in development. The FOG-M is such a weapon; it flies along near the ground at low speed, and the visible/IR scene in front of it is transmitted via fiber-optic cable back to an operator who commands the weapon in both search direction and in target and aim point selection. Fiber-optic cable places some constraints on the range and maneuvering of the weapon, but it eliminates the jamming susceptibilities of radio communications links and is cheaper. The panel envisions tht over the next 35 years, the range limit of fiber-optic cable might be extended to greater than 100 km.

3. *Automatic lock-on-after-launch.* This is getting into the autonomous weapon domain, but if the basket is constrained and the target type specified ahead of time, it probably avoids the worst fears about fully autonomous weapons. The main utility of this type of weapon is to attack mobile targets from long

range and from somewhat uncertain positions (50 to 100 m target location error). The long range relates to a time-late delivery, and the mobility of the target specifies the basket size within which it must be located. Smart submunitions carry out this type of attack already, using simple nonimaging sensors sometimes in combination within a constrained footprint. However, if there is any mixing of high- and low-value combatants or combatants with noncombatants (e.g., a transportable erector launcher [TEL] on a road or for combat near developed areas), some degree of target recognition will be needed, enough for example to distinguish a tank from a truck or a TEL from a bus. Such target sorting will require good night-imaging capability, i.e., probably a good-quality IR imager. Counter-countermeasure (CCM) capability is also required to defeat decoys and jammers. For fixed targets with uncertain absolute positions, weapons such as JASSM incorporating on-board autonomous scene-matching processing using IR, or advanced synthetic aperture radar (SAR), sensors are desirable.

MMW Technology

A similar technical theme is emerging in MMW technology: MMW imaging arrays using lithographically fabricated microbolometers. These yield modest resolution, all-weather imaging, which is low cost (no MMW circuitry), compact, and capable of penetrating many types of camouflage. They also yield without further effort capability in the 140-GHz and 220-GHz atmospheric windows, which are difficult to implement with millimeter microwave integrated circuit (MMIC) technology. This, like the low-cost IR imagers, should find a strong commercial market which will support rapid technical maturation and reduce procurement costs.

For weapon guidance MMW imagers are adequate to find and hit targets, but they do not offer the resolution of the IR imagers and may be less capable where there is a mix of military and nonmilitary objects or vehicles. An advantage they offer over the IR is a superior ability to see through obscurants.

Multispectral and Hyperspectral Optical Imaging Technology

Optical imaging technology in the multispectral (up to tens of wavelengths) and hyperspectral (hundreds of wavelengths) ranges is being intensively developed and offers enhanced capability to find targets in clutter and in camouflage, concealment, and deception (CCD) environments. Additionally, *multimode* sensors (various combinations of optical, IR, MMW, laser, and radar sensors, processed to yield a composite image, or even combinations of imaging and nonimaging sensors) are emerging into practicality as the costs and sizes of the component sensors diminish. This development is crucial, since it can be anticipated that the ingenuity and resources invested in CCD will increase in proportion to the effectiveness of our target-acquisition and destruction capabilities.

Currently, multi- and hyperspectral imagers are employed or conceptualized for use on search platforms (aircraft and satellites), and not on the weapons themselves. (Rudimentary multispectral sensors, e.g., IR plus UV, are used for decoy rejection in imaging seekers on some antiaircraft missiles, and this capability may be carried over into the imaging sensor versions coming up.) Size, weight, cost, and complexity make this technology inappropriate for integration into a weapon at this time. However, as CCD techniques improve and become ever more widely employed, it will become progressively necessary to incorporate the counter-CCD capabilities of multi- and hyperspectral imagers into the weapons themselves—particularly those weapons such as JASSM or smart submunitions that must localize and identify targets with the on-board sensors. The technology itself will undoubtedly progress toward cost and size reductions that at some point will permit this adaptation.

Multimode sensors are already in use in various weapons, for example the BAT missile, which employs both IR and acoustic sensors (nonimaging). Multimode imagers are presently too bulky for use on weapons, but it seems likely that the cheap and compact IR and MMW imagers under development will support such employment.

SAR Technology

Currently large and expensive, SAR technology is being advanced to the point where it can be deployed on bombs and missiles for course-following or terminal-homing employment. The seeker technology is not yet truly compact, so the initial employments are on large weapons. Significant reductions in size, weight and cost are already under way. The advantage of this type of imager is that it can see through clouds and smoke. It lacks the resolution of IR imagers but should provide a 3-meter CEP, which is quite adequate for most targets.

Three-dimensional Laser Imagers

These imagers are in development, and the addition of the third dimension to the image should be a major assist in target recognition and in precision-terrain following and navigation. These imagers operate by scanning a high pulse-repetitive frequency (PRF) laser over the target complex and measuring the reflection strength and the time of flight of each pulse. Present versions generate between 100,000 and 200,000 pixels per second, with 6-in.-range resolution. The natural evolution of this technology will be toward higher pixel rate and longer range (higher pulse energy).

Image-processing Technology

The previously elusive goal of automatic target recognition may become feasible with image-processing technology. Processing rates are climbing into

the teraflop domain, and factors of 10 to 100 beyond that are in sight. It may be a bit of a stretch to project autonomous weapons cruising over enemy territory, finding targets on their own, and destroying them; however, it seems less of a stretch if a human override authority is added to the picture.

The panel cannot postulate technologies that have not been invented. Nevertheless, the robust growth of sensor technology over the last 35 years cannot be ignored. There is good reason to suspect that within the time frame of this study new sensor capabilities will be available for weapon guidance.

Threat Responses

It is useful to look a step beyond these remarkable advances in sensors and the immediate combat advantage they imply and address the question of responses to that capability. There are several kinds of responses: emulation, countermeasures, and altering the combat forms to deny them leverage. Comment will be made on emulation and countermeasures; altered combat forms are beyond the scope of a sensor discussion.

Emulation, playing the same technologies back at us, is a simple technology race with advantage going to the fastest. The United States is clearly the fastest currently, and other nations largely play catch-up on what we pioneer. Unless we develop a serious high-technology rival in the future, our technology lead is likely to persist—assuming that we keep working at it. (It is worth noting that the technical lead in short-range, IR-guided air-to-air missiles was taken by the Soviets in the early 1980s, with the AA-11 Archer missile, and in the early 1990s by the Israelis, with the Python 4 missile. The United States will not recover competitive status in this matter until the deployment of the AIM-9X in 2002, at the earliest.) However, even Third-World nations will have access to sophisticated sensor systems through military sales by countries such as France, Russia, and the United States itself. The enormous single-sided advantage we held in Desert Storm because of our thermal-imaging systems is giving way as such systems, both capable and cheap, appear in both military and commercial markets.

Both passive and active countermeasures to sensors can be expected to proliferate as our combat capability becomes more closely wedded to advanced sensor systems. CCD techniques will become increasingly sophisticated, and laser and RF antisensor technologies may proliferate.

Many of the same weapon-sensor technologies that we look to for enhancing our strike capabilities will apply to air defense systems, and our ability to get weapons all the way to target will be eroded. In time, a premium will be placed on those strike weapons that are largely immune to short-range air defenses—saturation weapons, such as submunition dispensers, or weapons with very-high-speed terminal approach, stealth, or low susceptibility, such as kinetic-energy penetrators. Already we are witnessing the first deployments of defensive weapons designed to protect armor against antitank missiles (the Soviet Drozhd and

Irena systems, which are on the world market). Longer-range air-defense weapons designed to protect high-value targets against air-launched precision munitions are also appearing on the world market (the Russian Tor-M1, an upgraded SA-15). The effectiveness of precision-strike weapons is already producing the predictable response, and it seems likely that the utility of weapons such as the joint direct-attack munition (JDAM), joint standoff weapon (JSOW), and TLAM against high-value targets will not persist unless penetration technologies and tactics are seriously and successfully addressed. Technology can favor either offensive or defensive weapons. The element of surprise tends to rest with the offense, however, and the Navy must seek to lead in both offensive and defensive capability.

TARGETING AND STRIKE ARCHITECTURE

Background

The subject matter encompassed by the terms command, control, communications, computing, intelligence/surveillance, reconnaissance, and target acquisition (C^4I/RSTA) is so broad and so important to the future of naval warfare that an entire panel of this study (Panel on Information in Warfare) has devoted itself to these subjects. Although that panel has considered the specific evolving technologies that will change naval capabilities over the next 25 to 35 years, the Panel on Weapons found that it would be impossible to consider the future evolution of naval weapons and weapon systems without an examination of the targeting and strike support architecture needed to support various proposed future weapons.

In any engagement involving offensive strikes against an adversary, the theater commander-in-chief (CINC) establishes general target priorities and approves the allocation of weapon and platform resources.

During the Gulf War, the CINC established a joint forces air component commander (JFACC) who was delegated the following responsibilities:

- Control the use of theater air space and ensure deconfliction among friendly air assets (surveillance aircraft, refueling tankers, UAVs, search and recovery, logistic aircraft, strike aircraft, fighter aircraft, and so on);
- Assign ingress/egress routes and communication channels for strike aircraft;
- Provide fighter cover for high-value air platforms;
- Assign sectors for surveillance aircraft;
- Coordinate long-range missile strikes;
- Coordinate procedures for close air support with the joint forces land component commander (JFLCC); and
- Issue a daily air tasking order (ATO) that designates targets, time of attacks, and resources to be employed.

During the Gulf War, U.S. and consortium air operations were effective. However, the complexities of controlling all air operations proved to be stressful to existing software and communications systems. The panel believes that the functions assigned to the JFACC during the Gulf War will of necessity always need to be assigned to an equivalent commander; however, the procedures used to execute these functions will change.

The panel is persuaded that major evolutionary changes that will have an impact on strike warfare will occur in the existing architecture for C^4I/RSTA. The anticipated changes are listed below:

- Changes in weapons
  - Increased use of long-range, sea-launched missiles,
  - Increased rates of fire,
  - Improved weapon sensor and navigational capabilities, and
  - Data links;
- Improved performance of National,[20] airborne, and other sensors;
- Connectivity of adequate bandwidth to support rapid transmission of high-resolution imagery and other data; and
- Improved mission-planning software, computers, and displays.

The postulated changes in weapons, sensors, connectivity, and software will result in substantial changes in the architecture and procedures needed to support strike warfare. The future strike architecture that the panel envisages will commingle the functions of current air operations and artillery-control architectures. Because it may be possible to control and communicate with future weapons while in flight, substantial changes are foreseen.

Architectural Precepts

The concept of using sea-based firepower (either ship- or tactical aircraft [TACAIR]-launched) is not new. The panel believes that what will constitute a significant change will be an increase in the number of strike weapons that are launched from ships and a decrease in the numbers launched from aircraft.

The architectures that will be used to control future ship-launched strikes are likely to be variants of existing strike architectures adjusted for the management of new weapon capabilities. The following basic precepts for targeting and strike architecture are well established:

- The data-flow architecture should be capable of response to variants in
  - Target set,
  - Target density,

[20]The term "National" refers to those systems, resources, and assets controlled by the U.S. government, but not limited to the Department of Defense (DOD).

— Weapon mix,
— Battlefield topography, and
— Available platforms and other assets;

- Data-flow architecture should not limit the rate of fire of weapons;
- Real-time battle damage indication is essential to battle management; and
- Man-in-the-loop control will always be required at some point in the ordnance-delivery process.

Certainly, the data-flow architecture should be sufficiently flexible in its design that it allows easy reconfiguration based on variants in the target set, the target density, and the mix of available weapons. Other factors that will influence the architecture include line-of-sight distances to sensor and relay platforms and to and from weapons.

Sea-based firepower must be considered as a capability to engage both fixed targets and mobile or relocatable targets. Questions of weapon-release doctrine (e.g., shoot-look-shoot or shoot-shoot-shoot) can be dealt with only if preimpact target images or real-time battle damage indications are available.

Finally, it is emphasized that for the foreseeable future man-in-the-loop control and target designation will be necessary at some stage in the ordnance-delivery process. In addition to the rules of engagement (ROEs), the exact form and extent of human intervention will be dependent on available sensor technology, the capabilities of available data links, the weapon sensor's target-acquisition radius, and the weapon's capabilities for automatic target recognition.

From the standpoint of the strike-architecture design, there are only four target classes, designated as ephemeral, fixed, mobile/relocatable, and time urgent, as follows:

- *Fixed targets* are objects such as buildings, bridges, and railyards whose location can be established precisely.
- *Ephemeral targets* are those that "shoot and scoot" and thereby leave a limited period of time in which they can be attacked. Examples include the Iraqi-launched Scuds or North Korean artillery that rolls out of a deep cave, fires a shot, and then rolls back into the cave.
- *Time-urgent targets* are usually targets that must be struck to support engaged forces under current attack. The attack can be by some combination of infantry, artillery, or remote rocket fire.
- *Mobile or relocatable targets* include troops, tanks, trucks, self-propelled artillery and surface-to-air missile (SAM) batteries. Note that although targets in this category do move, they are not perpetually in motion. They often stop moving for periods that may be long compared with the time needed to fire a weapon at them.

Of the targets in this set, an architecture to support over-the-horizon attacks on mobile or relocatable targets using ship-launched weapons is the most difficult

to develop. Its feasibility is a function of many factors such as initial target-location error, weapon fly-out time, target-position update rate, target velocity, and the target-acquisition radius of the weapon that eventually impacts the target.

The architecture for support of attacks on fixed targets is well established. If cruise missiles are the weapons of choice, the problem is one of route planning to avoid topographic obstacles and enemy defense sites. If aircraft provide the initial means of weapon transport, the strike architecture must provide ingress and egress routes, refueling if necessary, communications links and procedures, combat air support, defense suppression, and so on. There exist a huge experience base and mature software that provide appropriate strike planning for air attacks against fixed targets. The panel foresees only evolutionary improvements in these areas. The only remaining problem in strike warfare against fixed targets is that in some circumstances the bandwidth limitations of currently available data links limit the amount of high-resolution imagery that may be transferred per unit time to strike planners. The panel makes the assumption that over the next 25 to 35 years the use of new technology and the results of new investments will result in the removal of factors that currently limit the rate of transmission of high-resolution imagery.

Architectures for close air support and for ephemeral targets are straightforward. Successful execution of these architectures generally depends on the instantaneous availability of TACAIR- or ship-launched weapons and command links that allow weapon release with little or no delay.

In the future, a battle manager (afloat) (BM[A]) will have some combination of extended-range guided missiles (ERGMs), long-range precision-guided rockets, cruise missiles, and TACAIR/precision-guided munitions (PGMs) at his or her disposal. The strike architecture should be such that the weapon and delivery systems chosen are those that are best matched to the target set.

Gun-launched ERGM rounds will have relatively short ranges of about 60 miles. If the vertical gun system (VGAS) is procured, it will provide a weapon with a range of about 100 nautical miles. However, both the ERGM and VGAS will deliver relatively modest warheads on their targets at their maximum ranges. On the other hand, they both have a high rate of fire and short fly-out times that make it difficult for a mobile target to evade attack.

Fast-strike precision-guided ballistic missiles will also have relatively short times of flight. For short target ranges, they would not need target location updates. However, as ranges increase, even these missiles may need updated target location data.

If cruise missiles are to be used in a tactical mode against remote mobile targets, the long times of flight involved for subsonic speeds require a system that can provide appropriate target updates. Such systems would be complex but appear to be technically feasible.

TACAIR has the advantage that it brings along a set of on-board sensors that,

after initial external cueing, allow target reacquisition and weapon launch. However, against mobile land targets TACAIR also requires considerable external surveillance support.

Whatever weapon system is chosen by a BM(A), it is clear that a strike architecture will be required that maintains accurate situational awareness for the BM(A) and for all subordinate weapon and sensor platforms and provides immediate strike damage indications to support reattack decisions. Four essential components of a sea-based firepower architecture are as follows:

- Target location, identification, and tracking sensors;
- Data-link connectivity from sensor-to-ground processing site (afloat);
- Mission-planning system for rapidly responsive TACAIR, cruise missile, and precision ballistic missile strikes, which includes
  - Connectivity with remote sensors for closed-loop control, and
  - Connectivity with TACAIR/cruise missiles for inflight updates; and
- Sensors and connectivity for target-damage indications.

First and foremost, a sensor system is needed that can provide target location, identification, and track. The output of these sensors must be tied via appropriate data links to an afloat processing site. If processing sites are available ashore, then processed data from these sites must be provided in real time to the afloat battle manager.

A mission-planning system is needed for TACAIR, cruise-missile, and precision ballistic missile strikes that permits rapid response to the situation ashore. If mobile targets need to be attacked at long ranges, the architecture must support closed-loop weapon control with the needed connectivity.

Finally, as indicated previously, connectivity to sensors that can provide the BM(A) with feedback reports of target damage is an essential component of the architecture. The design of the architecture must recognize that different classes of targets impose different functional requirements.

Fixed targets with known locations generally represent problems in the assignment of target priority and in the management of air and weapon traffic. BDA and the ability to make rapid reattack decisions are important components of the design.

For ephemeral targets, although connectivity to allow external cueing is necessary, unless high-Mach-number weapons are available, target sensing and weapon release must be co-located on the same platform.

Time-urgent and close-support targets require a system that allows target selection and designation by a local ground commander. In such situations, sea-based fire support serves the same function as division artillery and must be supported by a similar command net.

Mobile relocatable targets will generally require some form of closed-loop control along with supporting sensors and connectivity.

Sensors to Support Strike Architectures

A rich ensemble of sensor systems exists that can support sea-based firepower. Although the performance of these sensors may improve within the next 25 to 35 years, the panel believes that the functions performed by the classes of sensors listed above will not change. These classes have been divided into primary and secondary sensors. Primary sensors are those used by the BM(A) for situational awareness, for planning strikes by TACAIR and ship-launched weapons, and for assessing the impact of previously released weapons. Some of the primary sensors, such as those associated with National Technical Means (NTM), provide high-resolution data but cover a limited field of view. Other sensors such as electronic intelligence (ELINT) provide poor target-location accuracy but provide surveillance over huge areas. If data from all of the primary sensors can be fused together, then the BM(A) will be provided with excellent overall situational awareness. These primary sensors include the following types:

- Primary surveillance and bomb damage assessment (BDA) sensors
  - —National Technical Means,
  - —Theater sensors (JSTARS, Advanced Synthetic Aperture Radar System [ASARS], Guard Rail, UAV, Rivet Joint, and so on),
  - —Navy organic (SAR, inverse synthetic aperture radar [ISAR], electro-optical [EO], and so on),
  - —Third party (SOF, CNN, ground sensors, and so on), and
  - —Weapon sensors (via data link report-back);
- Secondary acquisition sensors
  - —TACAIR (forward-looking infrared [FLIR], SAR, electronic support measures [ESMs], EO, IR, visual) weapons, and
  - —Weapons (IR, acoustic, light detection and ranging [LIDAR], millimeter, imaging IR, and so on).

Secondary sensors include those on TACAIR platforms and weapons that allow them to acquire targets. As a general rule, if targets are not fixed, secondary sensors must be cued by primary sensors. The reason for this is that, although secondary sensors may have extremely high resolution, they have limited fields of view and except for the case of highly constricted battlefields cannot acquire targets efficiently without cueing.

The architecture must allow the primary sensors to be used to cue the secondary sensors close enough to a mobile target that the secondary sensor can acquire and kill that target.

Because cruise missile or TACAIR fly-out times may extend upward to 2 hours, the primary sensors must survive, be on station, and maintain connectivity among these weapons and platforms at least that long.

Architecture for Attacks on Fixed or Stationary Targets

The targeting architecture for fixed or stationary targets is simple and well understood and has been operational for many years. If adequate preconflict attention is paid to the target set, the target location error (TLE) will be zero. If, as may well be the case, a conflict situation arises with little previous history of potential conflict, target locations may be known incompletely or may be unavailable. In such circumstances, target locations must be established by a long and tedious process of imagery mensuration.

Under such circumstances, the TLE might be significant. As an example, suppose that a critical computer complex was known to be in a building with dimensions 100 meters by 60 meters, but its precise location within the building was unknown. Although the building's location might be known with extreme accuracy, overhead imagery would be of little help in establishing the precise location of the computer complex within the structure. In effect the TLE could be many tens of meters.

The overall architecture is invariant for both TACAIR- and ship-launched weapons. For TACAIR-launched weapons, the BM(A) must create a mission plan to allow for air traffic management and all of the necessary components of strike support. A mission plan is also required for ship-launched weapons. Among the principal components of the mission plan for ship-launched weapons is the damage-assessment function.

For fixed or stationary targets with zero TLE, both TACAIR- and ship-launched weapons are simply programmed to fly to the target's location. The accuracy achievable by combined GPS/IMU guidance is usually adequate. Generally, terminal guidance is only necessary where precise (less than 3 meters) aim point selection is required.

Reports of target damage are needed to allow an expedient reattack decision to be made. The frequent lack of bomb damage indication (BDI) reports is perhaps the BM(A)'s major problem with attacks on this class of targets.

Currently, there are a number of mechanisms for providing BDI, and the panel believes that the technology for providing it in the future will improve. Forward ground observers are among the most effective means for such assessments. In addition, damage assessment may be provided by TACAIR sensors, by sensors mounted on cruise-missile submunition dispensers, by organic reconnaissance aircraft, by UAVs, and by theater sensors. Perhaps the most effective damage assessment mechanism might be a sensor on a weapon that reports back its preimpact scene and GPS coordinates.

The issue is not the availability of sensors. The major limitation in existing systems is the lack of connectivity of adequate bandwidth between the report-back sensors and the BM(A).

Architecture for Attacks on Ephemeral Targets

No approved military definition of ephemeral targets appears to exist. As a practical matter, any target that can emerge from its hidden location (where it is both undetectable and invulnerable to weapon attack), set up to execute its mission and return to its sanctuary in a time that is shorter than the cycle time of U.S. forces for detection, classification, weapon-release decision, and weapon fly-out time, may properly be characterized as an ephemeral target.

An architecture for countering ephemeral targets must begin with a sensor strategy. Unless there are a priori reasons to know the general location of the sanctuary areas for these targets or unless these targets have a unique signature, they are very difficult to detect upon emergence from their sanctuaries. Fundamentally, sensors must be deployed continuously over the suspected target-sanctuary area. These sensors must have a wide enough field of view to cover any possible area of target movement and enough resolution to allow prompt detection, classification, and localization of the target.

Although ground observers can, under certain circumstances, provide the necessary surveillance, in general, a forward-deployed, loitering (manned or unmanned) airborne platform will be required to maintain this form of area surveillance. Because all-weather surveillance will be needed, the sensor will need to be either a high-resolution imaging or moving-target indicator (MTI) radar. Because the sensor is likely to be an active sensor, the platform it is on can be tracked and located by the adversary. Thus, the sensor platform must be protected by an appropriate form of combat air defense, which in turn must be supported by all of the necessary sensors, data links, and defense-suppression weapons.

If the sensor platform does not carry quick-reaction weapons designed to attack the ephemeral target on detection, data links must be established between the sensor platform and the weapon-release platform. Authority to release a weapon when the sensor platform indicates that it has met the necessary detection criteria must be predelegated to the weapon platform.

Systems designed for the suppression of ephemeral targets clearly would work best if the target sensor, the reaction weapon, and the weapon-release authority were co-located on the same platform. If it is not feasible to carry weapons on the sensor platform (e.g., because the sensor platform is a weight-limited UAV), then the weapons must be on either a separate aircraft or ship that is fully linked to the sensor platform with wideband connectivity to the detection platform so that weapon release authority can make an appropriate decision based on an assessment of the quality and nature of the detection. If in the future the sensor platform were to "forward pass" a missile launched from a separate platform, a link would be needed to the missile in flight.

For the immediate future, attacks on this class of target by ship-launched weapons will be limited to short-range situations. Available reaction weapons

will be limited to ERGM rounds and possibly ATACMS. In this case weapons with terminal-guidance sensors and GPS can be employed provided that friendly forces are not too close to the aim point.

If the precision-guided ballistic missiles discussed later in the section on surface and air-to-surface weapons of this report are developed and acquired, then the range at which ephemeral targets can be attacked will increase. The range at which ephemeral targets can be engaged is a function of the following factors:

- Target exposure time,
- Time to detect the target,
- Decision time for weapon release,
- Weapon fly-out time, and
- Distance between the weapon platform and the target.

As discussed in the section on surface and surface-to-air weapons, a rocket-boosted ramjet might deliver an average velocity of Mach 3 whereas a rocket-boosted scramjet might deliver an average velocity of Mach 6. A velocity of Mach 3 corresponds to a speed of approximately 60 km/min, and a velocity of Mach 6 corresponds to a speed of approximately 120 km/min. The time of flight to a target at a range of 600 km would be about 10 minutes for a Mach 3 weapon and about 5 minutes for a Mach 6 weapon. The ability to employ such ship-launched weapons against a remote ephemeral target will be a function not only of the range but also the characteristics of the ephemeral target.

The time of exposure of a Scud-like missile may be between 10 and 15 minutes. On the other hand, a North Korean artillery unit that emerges from a cave and fires several rounds may only have an exposure time of 1 to 3 minutes. Whatever weapons are used, if the response weapons are not co-located on the sensor platform, then high-bandwidth communications links will be required to support a weapon employment architecture that is information-intensive.

Architecture for Attacks on Time-urgent Close-support Targets

Traditionally, sea-based weapons have provided fire support for forces ashore. The architecture employed to support the engagement of time-urgent close-support targets by naval surface fire support was relatively simple. It was based on the presence of a forward observer who targeted a Navy surface ship. The impact point of the projectiles was observed and corrections were advised. The process was effective but limited. The range of Navy 5-in./54 guns was limited to about 13 miles, and the forward observer had difficulty establishing his precise location and that of the target. The communication links available for calling in and correcting the aim points were (and generally still are) line-of-sight voice links that are not overly efficient links for data transfer.

It is envisaged that in the future, although the basic architecture will be

retained, the process and the effectiveness of surface fire support for engaged forces ashore will improve greatly. The new technologies that will bring about these improvements are as follows:

- Surface fire support ships will be equipped with longer-range (~60- to 100-mile) weapons.
- Current data links will be augmented by the provision of beyond LOS connectivity with the ground observer. Either a man-portable satellite communications (SATCOM) link will be available or a battle group passive horizon extension system (BGPHES) aircraft will be employed as data-relay platform.
- Digital data links will be introduced that will enhance the ability of the ground observer to transfer target data.
- The observer will know his location in GPS coordinates and will have a laser range finder that will provide the target's range and bearing and thus its position in GPS coordinates.
- FLIRs and/or the equivalent of camcorders will be available that will allow the forward observer to transmit to the surface-support ship an image of the target he wants struck.
- Guidance for remotely fired close-support weapons will be based primarily on GPS/IMU guidance.
- Low-cost data links to the weapon will be available so that updated target locations can be passed to the weapon to compensate for the target's motion during the 3- to 5-minute fly-out time of the missile.

Although its value in a close-support situation is unclear, it is certainly possible to transmit an image of the target to the weapon in flight. If the weapon had a sensor that provided an image in the field of regard that included the target, then a digital scene matching area correlation (DSMAC) processor that compared the most recently received image of the target with the image provided by the weapon's sensors would allow extremely accurate terminal guidance. Such a system would be a derivative of the DSMAC system that has been used for many years in the terminal guidance system of the Tomahawk missile.

Simply put, the past problems involved in providing time-urgent fire support to engaged troops are all amenable to a solution with the application of currently existing technology. GPS, digital data links, image-transfer technology, DSMAC guidance systems, ERGM, and long-range precision-guided rockets should alleviate almost all past problems related to strikes on time-urgent targets.

TACAIR has long had an important role in the provision of close air support to engaged troops. Because of the difficulty of completely suppressing all components of the enemy's air-defense system, the trend in recent years has been to develop air-to-surface missiles that can be launched from safe standoff distances. As standoff distances have increased, the same targeting problems have been encountered that have been encountered in the surface-fire-support situation.

Fortunately all of the technology discussed in the preceding paragraphs is

directly applicable to TACAIR weapon delivery. If anything, the problem is simpler for the TACAIR case because as an elevated platform, its LOS is great enough that both SATCOM links and BGPHES relays will generally be unnecessary. The key to the use of standoff weapons on TACAIR platforms will be the availability of reliable connectivity between the ground observer and the TACAIR platform. As is the case for ship-launched weapons, the availability of a digital data link between the ground observer and the TACAIR platform would improve the efficiency of data transfer.

Architecture for Attacks on Mobile or Relocatable Targets

The panel has defined mobile and relocatable targets as a set of ground targets that included enemy troops located beyond the fire support coordination line (FSCL), tanks, trucks, self-propelled artillery, and SAM batteries. Although these targets are mobile, they move slowly compared with the speed of aircraft or weapons. In a conflict situation, military ground targets generally do not move much faster than 1 km/min. Note that although targets in this category do move, they are not perpetually in motion. They often stop moving for periods that may be long compared with the fly-out time of a weapon.

Although the use of TACAIR to attack mobile or relocatable targets beyond the FSCL is well understood and accepted, the concept of attacking mobile or relocatable targets beyond the FSCL with ship-launched weapons is relatively new and not fully accepted. Two incompletely resolved problems exist. The first is the ability to establish the identity of the target (combat ID), and the second is to hit a moving target that is over the horizon.

At present, there is no completely satisfactory means of establishing combat ID. Many techniques are used, but regrettably, as recently as the Gulf War, incidents of fratricide occurred. The issues related to combat ID are discussed in *Volume 2: Technology* of this study.[21] For purposes of this discussion, the panel finesses the issue by assuming that the sensor system that detects the over-the-horizon (OTH) target also establishes the target's identity prior to the call for ship-launched weapons.

In the past, existing weapon technology did not allow ship-launched ordnance to engage remote moving targets. Unless a data link to the weapon was available to provide continuous real-time closed-loop-control guidance, by the time a weapon flew to a remote aim point the target would have moved outside of the target-acquisition basket of the weapon's sensors. In effect, unless some form of a closed-loop guidance system was available, it was difficult for ship-launched weapons to hit a remote OTH moving target.

[21]Naval Studies Board. 1997. *Volume 2: Technology, Technology for the United States and Marine Corps, 2000-2035: Becoming a 21st-Century Force,* National Academy Press, Washington, D.C.

The advent of modern munitions and submunitions with sensors that provide a large target-acquisition radius and the possibility of ship-launched high-speed (Mach 3) surface-to-surface missiles gives the concept considerable credibility.

Nevertheless, situations will occur where closed-loop control of the weapon will be required. Basically, if the launch delay and fly-out time of the weapon is sufficiently long to allow a target to hide or move out of the acquisition basket of the sensors on ship-launched weapons, then target-location update information must be provided to an inflight weapon in order to vector it sufficiently close to the target so that the target can be acquired. Such an update system, which requires a line-of-sight data link, in effect, constitutes a closed-loop weapon control system.

Fortunately many circumstances will be encountered, where an open-loop control system will be adequate even for ship-launched weapons. In these situations, the target will not be able to move outside of the acquisition basket of the weapon's sensor before the weapon arrives in the vicinity of its initial aim point.

A real-time sensor-to-shooter-to-weapon closed-loop-control system will be required if the launch delay and time of flight are long enough to allow the target to hide or to move out of the acquisition basket of the secondary sensors on a TACAIR platform or on a weapon.

An open-loop-control system will be adequate if the launch delay and time of flight is too short to allow the target to hide or move out of the acquisition basket of secondary sensors on TACAIR platform or on a weapon. All things being equal, in an open-loop-control situation, the larger the acquisition radius of the munition's or submunition's sensor, the higher the probability of success.

Thus, targeting and connectivity to sensors and weapons are the central problems that limit the use of long-range ship-launched weapons against mobile targets. In general, as the target range increases beyond about 75 miles and the time of flight becomes several minutes long, the need for supplying target-update location data becomes more critical. A remote tracking sensor is required along with real-time connectivity between the surface platform, the weapon, and the forward sensor.

Another requisite for a successful sea-launched weapon system would be some form of real-time BDA report-back. This again implies connectivity between the surface ship and the weapon immediately prior to target impact. This link would need to have sufficient bandwidth to provide a reasonably complete report-back, so that the need to launch another round could be determined.

The communications bandwidth to support the update rates required for closed-loop weapon control should not stress existing data-link bandwidths. For example, suppose that the target is moving at 30 miles per hour. Then, if the sensor on the munition has a 2-mile acquisition radius (as in the case of the BAT submunition), a location update will be needed only every 4 minutes of fly-out time. If the sensor's acquisition radius is only 200 meters, the munition must be updated every 12 seconds.

Estimating that a 600-bit message is necessary for a target-location update, the required data rate would only be 50 bits per second. In general, the situation will be more complex. The target may include many autonomous objects, and the weapon may carry multiple independently targeted submunitions. As an example of a moderately stressing case, if there were 168 independently moving targets and the sensors required a 12-second update rate, a data link with a 9.6-kilobit transmission rate would be adequate.

The limiting problem is unlikely to be the amount of data that must be passed. The ultimate limitation may be the ability of an external primary sensor such as JSTARS to track a large number of individual mobile targets.

Defensive jamming of the weapon-control data link could be a substantial problem. The fielding of a data link that is robust against plausible levels of jamming might require a link with an antijam margin that is comparable to that incorporated into the Joint Tactical Information Distribution System (JTIDS).

Real-time report-back of a weapon's preimpact field of view (FOV) is exceedingly important to a BM(A) who must control the expenditure of a finite inventory of expensive weapons. Although poststrike reconnaissance imagery is still needed, it is no real substitute for weapon report-back.

The 16-kilobit AWW-13 link is the only link currently available for incorporation into new weapons and submunitions. The AWW-13 is an adequate link for the purpose even without the use of compression techniques. The use of data compression would allow various tradeoffs of resolution, field of view, number of gray scales, and so on. In effect, the weapon data-link problem has been solved for some existing weapons. The solution can in principle be incorporated into other weapons. The principal problem facing future weapon system designers is the cost of a data link such as the AWW-13. The panel is optimistic that the current high cost of broadband two-way weapon data links will be reduced by the application of future advances in technology.

The remaining problem in the case of long-range ship-launched weapons is connectivity between the sensor and the shooter in the case where the shooter is a remote ship. A number of solutions to this problem are possible. In the case of submunitions, the report-back connectivity would be via the submunition transporter to the last platform that had LOS connectivity with it and, thence, back to the BM(A).

The basic component of the architecture needed for a ship to attack over-the-horizon mobile targets is a data link that enables an external sensor to feed information to an afloat data-processing center whose output indicates to the BM(A) the need to release a weapon at a remote target. Without a robust data link between the remote ship and the external sensor, there would be little likelihood that the ship could attack remote mobile targets. The panel assumes that, over the next 25 to 35 years, all existing problems of connectivity between a BM(A) and the remote sensors that provide him remote target information will be resolved.

When TACAIR platforms are used to attack distant mobile targets under circumstances that require closed-loop control of the weapon, the system architecture will be similar to the ship-launched weapon case. Two architectural variants are possible. The TACAIR platform may function both as a weapon-transport system and as a relay node. An external sensor such as JSTARS monitors the target and sends update messages to the weapon via the TACAIR platform, which must maintain LOS connectivity with the weapon from the time of release to the time of impact. Prior to impact the weapon reports back the preimpact scene detected by its sensor. This closed-loop concept places little demand on the sensor suite of the TACAIR platform. Indeed, this concept of closed-loop weapon control would not even require the TACAIR platform to acquire the target prior to weapon release.

A variant of the previous closed-loop architecture is feasible. The difference is that in this variant the sensors on the TACAIR platform would be sufficiently competent that, after the aircraft has been cued by an external sensor, the aircraft's own sensors can acquire, identify, and maintain continuous track on the target set from safe standoff distances.

When weapons are launched under circumstances that require closed-loop control, the TACAIR platform generates the necessary update data and forwards them to the weapon in flight. This concept makes maximum use of a man-in-the-loop in the sense that, except for the cueing function of external sensors, all weapon-release decisions and target-update data are generated in the TACAIR platform. The architecture for an open-loop control system is fundamentally the same for both TACAIR and ship-launched weapons. An external sensor alerts the BM(A) to the existence of targets. This architectural concept is based on the assumption that circumstances may arise that will permit a GPS-guided weapon to arrive close enough to a mobile target that the target-acquisition sensor on the weapon will allow the weapon to acquire and kill the target.

An example of this type of situation might be when the weapon is a gun-launched ERGM-type round or the equivalent of an ATACMS carrying BAT submunitions and where the target is a set of slowly moving or stationary tanks with their engines running. In the case of ATACMS, the time of flight might be about 3 minutes or less. During this relatively short time span, the target may not have moved very far. If the submunitions on the ATACMS is a BAT, and if the BAT performs as advertised, the BAT will acquire the target, provided the target has not moved outside of an area of about 12.5 square miles centered at the original aim point.

Summary

Although all of the problems in weapon design are far from being resolved, the panel is optimistic that with the application of currently available and projected future technology, strike architectures can be developed that will allow

both air- and sea-launched weapons to engage on a routine and effective basis the following types of targets:

- Fixed targets,
- Ephemeral targets,
- Time-urgent close-support targets, and
- Over-the-horizon mobile or relocatable targets.

Achievement of these capabilities will require the development and acquisition of data links that allow such functions as:

- All naval strike platforms to receive appropriately processed data from all of the primary surveillance and BDA sensors listed previously,
- Updated data to flow to weapons and preimpact imagery to flow back from weapons, and
- Digital messages and target imagery to be passed from forward ground observers to strike platforms (both surface and air) and to weapons in flight.

In addition to the necessary links and connectivity for targeting, weapon sensors and guidance systems will be required that are as follows:

- Robust in the presence of GPS jamming (low-cost, low-drift IMUs),
- Able to operate in a DSMAC mode using imagery provided by a forward observer, and
- Equipped with wide-FOV sensors to allow them to acquire targets that have moved during the weapon's fly-out time.

The foregoing discussion indicates that the design of weapons, whether sea- or air-launched, must represent a successful integration of the target identification and location process, the nature of and range to the target, the weapon-guidance process, the weapon sensor's field of view and resolution, and data links to and from the weapon.

GUIDANCE AND CONTROL

Background

Since the mid- to late 1970s, the U.S. Navy has relied predominantly on aircraft-delivered laser-guided munitions (LGMs) for the precision strike of ground targets. The Navy employed the AGM-123 known as Skipper II (a variant of the Air Force's Paveway II) with the Pave Knife laser designator. The actual Navy weapons were the GBU 10 E/B Mk(84), the GBU 16 B/B Mk(83), and the GBU 12 D/B Mk(82). These weapons were used on Navy A-6s, A-7s, and F-14s and on Marine Corps AV-8s. In the last decade, the ship- and submarine-launched cruise missile (SLCM) has provided a long-range augmentation to aircraft, but the numbers are expected to be a small fraction of aircraft or

ballistically delivered ordnance into the foreseeable future. The LGM was originally conceived as a man-in-the-loop weapon where target acquisition and precision delivery are effected by the pilot using targeting aids on the strike aircraft. A logical expansion of the LGM operational concept would be for the target acquisition and laser illumination functions to be provided by a UAV at relatively close range to potential targets and under the weather so that the aircraft can operate outside of the air-defense envelope and maintain overall control of the weapon through the use of a data link. Technologically, this should be easy to implement although the problem of coordinating strike aircraft with UAVs, especially for long-range strike, may not be simple. In fact, experiments have been conducted by the various services to evaluate this concept. It may be useful to consider an extension of the LGM concept to the delivery of a ballistic laser-guided munition (BLGM) using the cheap modular rocket-delivery systems discussed elsewhere in this report where targeting and laser illumination are, once again, affected by a UAV. In this case, a higher bandwidth communications link will be required from the UAV to the BLGM launcher to transfer imagery for the IFF function and target selection.

A variation of the video homing weapons (Walleye, Rockeye, and the like) that is under development for aircraft delivery is the JSOW. The JSOW uses a passive infrared focal plane for precision homing and delivery of a munition and could be used in a launch-and-leave mode or with a data link so that the pilot can make corrections, if need be, in final target-aim point selection.

This capability can be used with a form of guidance known as fire on coordinates where initial targeting is provided by an off-board sensor and the weapon is directed after launch into a basket using GPS or INS, or both. The seeker would then, with or without command guidance, provide final corrections. The JDAM, an air-delivered weapon that relies only on GPS/INS for guidance, is also under development and procurement by the Department of the Navy. Clearly, as in the case of the BLGM, these guidance concepts could be incorporated into ballistically delivered weapons where the surveillance and targeting information is provided by UAVs or other platforms and the necessary information sent over communication links to the launch platform.

A further potential derivative of the JSOW is the utilization of the target surveillance information, especially if it is in the same modality as the weapon seeker, to provide a lock-on-before-launch capability for the seeker that could then operate as a correlation tracker and provide a near-optimum probability of target acquisition and aim point selection. If the surveillance sensor and seeker operate in different modalities, a translation would be required. It is clear that this technique would require wide bandwidth for information transmission on demand, but future trends for battlefield communications should insure that capability.

An important technical consideration in any future conflict involving naval forces is the mix of weapon types (unitary, penetrating, fragmenting, and cluster bomb) and guidance packages (such as those discussed above) that should be avail-

able on station. For example, if a ship is an arsenal that is loaded in port, it may not be practical to change the weapon load at sea. In that case, it is important to carry weapons in proportion to the types of targets that intelligence sources estimate will be encountered in the theater of operations. It will be assumed that precision terminal homing (on the order of 1 to 3 meters) will drive up the cost of a weapon compared with the cost of accurate weapon delivery (3 to 10 meters), and the guidance option should, thus, be matched carefully to intelligence estimates.

During Operation Desert Storm, U.S. and coalition aircraft conducted over 35,000 strikes against targets in Kuwait and Iraq.[22] In general, 75 percent of these targets were against mobile/relocatable targets composed of Iraqi ground forces and the remaining 25 percent were characterized as large fixed targets. The weapons varied from unguided bombs to LGMs. It is assumed that the naval forces will be assigned some fraction of the total target set in a future conflict and will employ only guided munitions and that these munitions will be delivered by rockets to the appropriate target baskets. The fixed targets include bridges and hardened revetments that will require accuracies of 1 to 3 meters that can be derived from sensor seekers or, perhaps, differential GPS, which is discussed below. Buried bunkers will require penetrating weapons with a similar accuracy but different warhead configuration. The preponderance of large fixed targets can be neutralized by using GPS or differential GPS and/or INS with appropriate warheads.

The mobile targets vary from hard (tanks, armored personnel carriers) to soft (trucks, TELs, and fuel carriers). Although mobile, these targets are also stationary for extended periods and if the time from surveillance to targeting can be reduced to the response time of a rocket, then these targets, hard and soft, can be engaged using cluster munitions, scatterable mines, and other area weapons with some form of GPS/INS guidance. If the targets are in motion, a method of updating the rocket aim point in flight is needed to reduce the search demands on a terminal seeker for hard targets. For soft targets, the requirements are relaxed somewhat and cluster munitions can be used.

A typical tactical missile cost breakdown[23,24] is as follows: seeker (40 to 50 percent); navigation (25 to 30 percent); warhead/fuse (5 to 10 percent); propulsion (10 to 15 percent). If we associate GPS/INS with navigation, then a rule of thumb appears to be that a seeker will double the cost of a missile to a first approximation although technology breakthroughs may reduce this number. For-

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[22]Cohen, E., and T. Kearney. 1993. *Gulf War Air Power Survey Summary Report,* Vol. 14, U.S. Government Printing Office, Washington, D.C., fig. 12, p. 65.

[23]Crouch, J., and T. Bowman. 1996. "EO/IR for Affordable Strike Warfare," *Proceedings of the Second NATO/IRIS Joint Symposium,* held in London June 25-28, Infrared Information Analysis Center, University of Michigan, Ann Arbor, Mich., and Technical Paper OR21292, Lockheed Martin Corporation, Orlando, Fla.

[24]Habayeb, A.R. 1997. "U.S. Naval Inertial Guidance Science and Technology Precision Strike Navigator," Naval Air Systems Command, Arlington, Va., presentation to the Panel on Technology, January 28.

tuitously, the bulk of perceived naval force targets should be subject to attack by a combination of navigation and communication technologies that are on the technological horizon. It is important for the Navy to conduct detailed targeting analyses to determine the final mix of weapons for its future delivery platforms. There is a potentially large cost savings to be realized in selecting the proper mix of warheads and guidance.

Global Positioning System

The Global Positioning System (GPS) provides highly accurate position, velocity, and time information to users anywhere in the world. The GPS operates by the use of a constellation of ultimately about 24 satellites in 12-hour (19,000-km) orbits that continuously broadcast their identification, position, and time using specially coded signals. Triangulation from at least four satellites is required for accurate results.[25]

GPS accuracy is governed by several system characteristics. These include constellation geometry, navigation message prediction accuracy, range measurement accuracy, and atmospheric effects. The typical absolute GPS error budget from noise and bias sources using the P-code (nonmilitary) results in a horizontal CEP of 5.2 m[26] although a CEP of 10 m can be expected under some conditions. The use of military codes results in a CEP in the 1- to 3-meter range although the use of differential techniques can assure absolute accuracies of 1 m or better.

A protocol known as Radio (Broadcast) Data System, or R(B)DS, used in conjunction with powerful FM radio stations is being used to offer commercial differential GPS service worldwide. According to information from Differential Corrections Inc. of Cupertino, California, the company offers service yielding a differential accuracy of better than 1 m. Given the range of proposed military and commercial improvements to GPS over the next decade, it must be assumed that precision characterization of target location will be readily available for use by surveillance sensors to establish targeting aim points. This assumes the absence of jamming that could deny GPS use near potential targets or the jamming of communications links that would prevent transferral of target location information to weapon platforms.

[25]Schmidt, G. 1996. "GPS Current Accuracies, Improvements and Targeting," C.S. Draper Laboratory briefing to the Panel on Weapons. Based on a May 1996 GPS/JPO briefing and a report by the Committee on the Future of the Global Positioning System (National Research Council, 1995, *The Global Positioning System, A Shared National Asset,* National Academy Press, Washington, D.C.), as well as other sources.

[26]Schmidt, G. 1996. "GPS Current Accuracies, Improvements and Targeting," C.S. Draper Laboratory briefing to the Panel on Weapons. Based on a May 1996 GPS/JPO briefing and a report by the Committee on the Future of the Global Positioning System (National Research Council, 1995, *The Global Positioning System, A Shared National Asset,* National Academy Press, Washington, D.C.), as well as other sources.

Inertial Measurement Unit

There is a great deal of ongoing work sponsored by DARPA and the Services to develop combined GPS/IMU systems.[27] The motivation is that if GPS is jammed after weapon release, then the IMU will provide guidance to the target. At the present time, weapon-grade IMUs develop about 1 degree per hour of drift. Current research predicts the availability of IMUs with a drift of 0.003 degrees per hour.

For weapons of less than 1 hour of flight, a drift rate of 1 degree per hour (current technology) would require a terminal reacquisition seeker of about 2 degrees field of regard. Such a seeker would require minimum processing for false-alarm rejection and target reacquisition. Emerging sensor technology discussed in the next section (Munitions Counter-Countermeasures) will provide the capability to build such a seeker. On the other hand, an IMU with a drift rate of 0.003 degrees per hour would provide guidance over a 1-hour-long 1,000-km flight such that at 1 km to impact the basket error size would be about 2 degrees or 30 m.

A logical strategy for the Department of the Navy might be, therefore, to concentrate on the development of low-drift-rate IMUs, use differential GPS at sea away from jamming sources to initiate the IMU, and avoid consideration of GPS jamming at the target terminus for the class of weapons discussed previously that will be used to fire on coordinates.

Man-in-the-Loop

As noted earlier in this report, if the naval forces adopt rockets from sea platforms as the primary fire support for precision strike, then aircraft-delivered weapons that require a man-in-the-loop will gradually diminish in numbers. These weapons characteristically utilize laser illuminators or radio links in conjunction with on-board seekers for command guidance. In the case of ballistic weapons, the man-in-the-loop character will derive from the human control exercised over IFF and weapon release throughout the whole process of surveillance, targeting, tasking, precision-weapon delivery, and damage assessment. Clearly, this will be a computer-aided process and is an element of what is commonly called aided target recognition or ATR.

MUNITIONS COUNTER-COUNTERMEASURES[28]

Another challenge that will assume increasing importance in future warfare is assuring the performance of guided munitions in an environment with effective

[27]Barbour, N., and G. Schmidt. 1996. "Inertial Sensors/GPS Technology Trends," C.S. Draper Laboratory, Guidance Technology Center, Cambridge, Mass., presentation to the Panel on Weapons, June 18.

[28]Information on air-to-air and air-to-ground CCM extracted from the Air Force *New World Vistas* study, Munitions Panel Report by M. Schatz and A. Brown.

countermeasures. One can expect advanced countermeasures to proliferate to the Third World: the Gulf War highlighted the importance of countering U.S. air-to-ground guided munitions. Countermeasures to air-to-air guided missiles (e.g., flares) have been widely deployed for some time. One important historical lesson about countermeasures is that every system can be countered in some fashion and potential enemies will continue to field new countermeasures. Thus, developing counter-countermeasures (CCMs) for existing munitions should be a continuing activity of the Department of the Navy.

Countermeasures to guided munitions fall into several classes, each class of which has its own characteristic CCM. The first class is active defense, that is, shooting the munitions. Passive defenses attempt to make a hit tolerable; examples include armor, underground structures, and redundant hydraulic lines on an aircraft. Signature control seeks to deny a munition's seeker the signature it requires to guide. Although camouflage is as old as warfare, modern signature reduction technology, primarily applied to aircraft and surface vehicles, is highly complex. Currently, likely adversaries cannot employ signature reduction effectively; however, efforts at signature reduction in Europe and Russia suggest we will need to deal with this technology. A related countermeasure is the use of obscurants to hide the signature of a target. These can be either generated (like smoke) or natural (like clouds). The widest class of countermeasures is inband electronic countermeasures (ECMs). These are systems that attempt to deceive or blind the seeker using energy or signals within the seeker's pass band. These include many well-tried techniques like noise jamming, flares, and gate-stealers.

The increasingly high reliance of the naval forces on electronics technology for its communications, computing and information processing, avionics, guidance, navigation, and control and for its command and control systems makes its warfighting capability even more susceptible to ECM countermeasures. This is especially an issue with the increased reliance on commercial electronics which, although inexpensive, do not have the countermeasure hardness that previously has been available in some special military electronics. Technology has progressed sufficiently in the past decade outside the United States to make development of practical weapons using ECM to upset or substantially degrade these electronic circuits very likely. An enemy countermeasure with this capability could cause major disruption in our modern warfighting capability if successfully deployed against our systems. This situation should make the development of CCM to this capability a priority activity. This should include as a minimum: programs to understand and model the phenomena; evaluation of susceptibility of current systems to ECM; and development of hardening techniques including shielding, design approaches, and exploitation of new materials and processes with lower susceptibilities.

In addition to countering the munitions, an adversary can attempt to counter other components of the weapon system such as acquisition and fire control sensors and the launch platform. Although dealing with these countermeasures is

not a munitions issue, the vulnerability of the launch platform leads to a preference for launch-and-leave weapons with as large a standoff range as possible.

Concepts

When a CCM is considered, one must remember that the countermeasure operates as part of a system. This may contain, in addition to the countermeasure itself, a deployment vehicle, an acquisition pointing and tracking (APT) system, and intelligence and cueing support. Disrupting any of these components can defeat the countermeasure. In particular, since many classes of countermeasures require APT systems, these can be attacked by reducing the signature of the munitions. For air-to-air munitions, the key signatures are the IR and ultraviolet (UV) plume and the body IR signature. IR and RF signatures are key for air-to-ground munitions. For optical munitions the optical augmentation signature is important. The panel will consider CCM for air-to-air and air-to-ground separately followed by consideration of CCM for acoustic torpedoes.

Air-to-air Missiles

For air-to-air missiles, passive defense is not a viable approach. Aircraft carry limited armor, and warheads are now, and presumably will continue to be, designed for maximum lethality.

Active defense against air-to-air missiles is not currently done, but presumably an active defense would be a self-protection missile. One can either defeat the APT or outmaneuver the interceptor, which is likely to be marginal. Defeating the APT would be accomplished by reducing the signature of the missile.

There are a number of types of inband ECMs, each with its own CCM. For IR missiles, the conventional ECMs, like flares and flash lamps, are designed to defeat reticle (and pseudoimaging) seekers. New seekers, like the AIM-9X, will use staring imagers; these will defeat flare and flash lamp countermeasures. The inband countermeasures to imaging seekers are high-power lasers. CCM techniques include defeating APT systems, careful optics design to reduce scatter, filters to block the laser lines, and home-on-jam.

For radar seekers there are several classes of important inband ECMs. The first class includes devices like gate stealers, which attack the tracking circuitry of the missile without angle deception. These are countered by traditional signal processing CCMs. The next class is expendables. Passive expendables like chaff and blivets are rejected by Doppler. More advanced forms, like illuminated chaff and active expendables, are also in use and can be rejected when they separate from the aircraft. The next class is high-power systems like Cross Eye and Cross Pole that disrupt or break angle track. These can be countered by signal-processing techniques or home-on-jam.

The final class involves endgame angle deception countermeasures such as

towed decoys and terrain bounce. This is the most difficult for CCMs, since the Doppler can match the target and the fast target stays with the target. Countermeasures currently being deployed outside the United States include systems on cruise missiles. The most primitive implementations can be defeated by signal processing, like range gating, but more advanced implementations will have to be discriminated in angle. This can be done by either superresolution or a dual-mode seeker, with the second mode (probably IR) having enough angle resolution to discriminate. The latter is the approach taken by the Navy's Missile Homing Improvement Program (MHIP). Superresolution techniques seem promising and will likely work for conventional aircraft. For the signal-to-noise ratio typical for cruise missile engagements, a superresolution seeker will have to move to the Ka-band. Therefore, the pursuit of dual-mode and superresolution seekers would be a logical step for the Department of the Navy.

Air-to-ground Munitions

For air-to-ground munitions, passive defense and burying or armoring the target are key countermeasures. Active defense against cruise missiles is a subset of the air-defense problem. Active defenses against bombs are not a current threat.

Signature reduction of ground targets against SARs or imaging (passive or active) optical sensors is not practical, except in limited circumstances. The IR signature of a vehicle can be reduced enough to defeat nonimaging IR seekers, but these are becoming obsolete.

The related area of obscurants is a key countermeasure. Operating under clouds or smoke will defeat our current PGMs, which are optically guided as was highlighted during the Gulf War. There are several candidates for seekers that can operate through these obscurants while still providing 10-ft accuracy. One choice is to continue using optical munitions but increase the agility of the airframe so that it can divert to the target when it can detect it through the obscurant (say 100 m away). For all-weather precision seekers, several options make some sense.

RF seekers are the natural choice for penetrating weather and smoke but have some drawbacks. Real-beam seekers must either operate at W-band and higher frequencies, where components are not readily available, or require such large amounts of beam splitting that the necessary signal processing has not been fully developed or tested (or both).

Synthetic aperture seekers have been developed and tested "captive carry" (carried by/on bomb itself) in the Advanced Synthetic Aperture Radar Guidance (ASARG) program and will be evaluated further under the Hammerhead Program.

There are, however, a number of difficulties with SAR seekers. The primary one is that to get accurate resolution for the SAR, the munition must move cross-range to the target. Thus, the munition will have to fly a dogleg toward the target

and must go inertial for the last leg. This means the accuracy is degraded by INS drift. There are also cost and targeting issues. Another approach has been to put the SAR on an aircraft and use that to direct the bomb, either by command guidance or semiactive means. These functions will be carried out at a greater distance, and so higher resolution must be achieved, which is a strong technical challenge. GPS may be a possibility using either a differential or a relative navigation scheme. The vulnerability of GPS to jamming in the terminal area must be offset by the use of one or more means. The use of Pseudolites is one approach to negating the effects of GPS jamming. To achieve 10-ft accuracy with current low-cost IMUs requires that GPS lock be maintained so close to the target that it is probably not cost effective. However, dramatic improvement in either low-cost IMU performance or adaptive antenna performance might make this an attractive option.

The inband ECM that might be used against air-to-ground missiles, of course, depends on the nature of the seekers. One approach is to use a mix of seekers so that no one countermeasure is effective against all of them. The adversary will be discouraged from deploying systems that operate only against a fraction of the potential munitions, and there are munitions that will function despite the countermeasures.

To defeat link jamming, one can employ more jam-resistant links, including more use of spread-spectrum techniques. To beat deceptive paint schemes, for example, a paint that is uniform in visible bands but a checkerboard pattern in the 8- to 12-μm region, we can use inband IR imagery for targeting or by using algorithms incorporating machine intelligence. To harden laser-guided bombs against repeater decoys like the one being marketed by GEC-Marconi, the Navy could use the pulse intermodulation (PIM) codes available for Paveway III. To defeat more sophisticated decoys the Navy should consider the improved ECM such as those of the Army's Hellfire II. To beat laser jammers one can reduce the signatures of munitions.

The low power of the satellite signal broadcast makes GPS particularly susceptible to jamming. Pulse, CW, broadband noise, and spoofers can disrupt precision navigation operations that rely on GPS.

There are two different classes of approaches that can be taken to counter GPS countermeasures. The first is to enhance the GPS receiver and antenna design to improve the jam-to-signal ratio (J/S) margin. The second is to provide a backup capability to allow precision targeting when GPS is disabled close in to a jammer.

Enhanced Antijam Receiver Performance

Sophisticated antijamming techniques under development for GPS offer significant improvements in J/S over the existing fielded equipment. Improved antenna design and digital filtering and signal processing techniques that take

advantage of advances in electronics can provide cost-effective solutions for next-generation military GPS receivers.

Potentially, antijam receivers that can operate with J/S up to 120 dB could be developed and put in operation within the next 5 years. With 120 dB J/S margin, operations can be sustained with relatively high-power jammers (e.g., 1 kilowatt) to within 100 meters of the jammer.

Backup Navigation Sources

Since even the most sophisticated antijam GPS receivers are susceptible to high-power jammers close to a target, a backup navigation system is needed for precision close-in navigation. Backup navigation can be provided by an on-board inertial system, from another unjammed radio-navigation source, or through the use of data from imaging sensors on the munition.

Microelectromechanical IMU

Microelectromechanical (MEM) inertial measurement units (IMUs) are under development that will provide a low-cost, single-chip autonomous navigation solution. In the near term, only low-grade navigation systems are feasible. When integrated with GPS, precise navigation can be provided over only short periods of time following GPS dropout. In the future, some of the advanced MEM sensors under development, particularly those involving superconducting materials, could provide performance equivalent to existing ring-laser-gyro (RLG) inertial systems with drifts of less than 0.01 deg/h.

Backup Radio-navigation Systems

Precision navigation can be maintained close in to a GPS jammer by using alternative radio-navigation sources as a backup. Any broadband signal broadcast can provide data for navigation if it is synchronized to GPS time, either directly in the data modulation or through differential corrections in the data for the signal time offset.

Radiolocation techniques have been demonstrated by the civilian community using triangulation and trilateration from such diverse signals as cellular transmitters, frequency modulation (FM) radio stations, and television broadcasts. Accuracies down to 100 meters have been achieved. Significant improvements in accuracy are possible through the use of broadband signals broadcast from geostationary or low Earth orbit (LEO) satellite systems, such as direct broadcast television, Immarsat, Iridium, or Teledesic. Signals broadcast from commercial or military satellites, from Pseudolites, or from UAV platforms can provide an adjunct or backup service to GPS over a theater of operations.

Commercial technology advances will allow low-cost, miniaturized fre-

quency-diverse receivers to be developed that can process different signal types over a broad range of frequencies. Multimode receiver designs that can use alternative signals as radio-navigation sources provide an effective counter to GPS countermeasures.

Imaging Sensor Guidance

Future smart munitions will use low-cost, miniaturized imaging sensors, such as video or IR lasers, to provide automatic target recognition (ATR). These sensors can also support guidance and navigation in the vicinity of a target. A database of recognizable features can be used to update the munition's location and provide guidance to the actual target. This terrain recognition capability would also offer a low-cost navigation capability close in to a target when GPS is jammed.

Acoustic Weapons

Current torpedoes are either wire guided or autonomous after launch. Onboard active and passive sensors may be susceptible to a broad range of spoofing devices or even antitorpedo torpedoes.

Future torpedo designs can incorporate off-board sensor information through the use of an optical fiber or through wide-band acoustic transmitters. Since the torpedo can be linked to the acquisition and track sensors on the launch platform and, in some cases, netted to fleetwide airborne, surface, and undersea distributed sensors, the torpedo can thus be controlled by an "underwater CEC." This utilization of distributed, multimodel instrumentation can be used to defeat countermeasures used for offense and defense purposes. In addition, providing torpedoes with a high-speed (200 knot) dash capability, using supercavitating fluid dynamic properties, will limit the time available to deploy and use effective countermeasures.

3

Surface-to-Surface and Air-to-Surface Weapons

BACKGROUND

The panel believes that 25 to 35 years in the future, unless limited by treaty, all air- and ship-launched attacks on fixed structural targets (buildings, transportation nodes, and age and fabrication facilities) will be undertaken with precision-guided rockets. Although the unit acquisition cost of such high-performance weapons will continue to be relatively high, a complete calculation of the true cost of target destruction using short-range, direct-attack, air-launched weapons in the presence of a competent and unsuppressed air defense system by recoverable (but attritable) aircraft, will drive the economics of such weapon delivery systems to the increased use of standoff missiles launched from aircraft, surface, or subsurface platforms.

Employing currently available technology, it is possible to build a new generation of much less expensive precision-guided ballistic strike missiles that would provide an attractive alternative to the present mix of cruise missiles and relatively short-range air-to-surface weapons. The rapid evolution of targeting techniques and low-cost geodetic guidance when combined with promising approaches for producing cheaper solid rocket motors might lead to major cost reduction for precision-guided rockets.

Future precision-guided rockets can be designed to be compatible with current ship and attack submarine vertical launchers and could be launched from many types of naval aircraft. The economics of these new types of missile would be attractive. In addition, they would be very difficult to defend against and would provide quick strikes against time-urgent targets, including some types of

relocatable targets. Also, even at shorter ranges, the missile's reentry velocity is high enough to defeat many classes of hardened targets with the use of kinetic energy penetraters.

During the era encompassed by this study, weapons will need to be precise and only affect their intended targets. The killing or wounding of local civilians as an unintended consequence of an imperfect attack on a legitimate military target will be unacceptable. Future weapons must be precise and must be designed to kill only the designated target. In addition to being precisely guidable to the intended targets, weapons must be designed for high levels of reliability.

As one of the presumptions of its deliberations, the panel has assumed that the United States will maintain an effective surveillance system that will provide assessments of the value of attacking individual target aim points and will be capable of providing precise locations and current images (visual, radar, or IR) of targets. Where targets are mobile or ephemeral, the targeting system will provide the last known target coordinates and the projected location of the target when the weapon arrives at the projected point of engagement. In addition, target signatures and images will be provided to the weapon so that, when a potential target is acquired by a weapon's sensor, it may be compared with the most recently updated signature in the weapons database.

In this study the panel began with a review of the fundamentals of propulsion chemistry, electromagnetic launch technology, explosive yields, and guidance and control technology. Based on its assessment of the relative advances that might be achieved in some of these areas of technology, the panel concluded that significant changes will occur in the configuration of sea-based weapon systems of the future.

The panel foresees that manned strike aircraft or command-guided UAVs will be retained for missions where the use of precision-guided rockets is infeasible. Following are examples of such missions:

- The target is ephemeral in nature with exposure times that are less than the time of flight of a hypersonic missile from its sea-based launch point to the target location. In such situations, long-endurance cruise missiles or recoverable airframes (manned or unmanned) equipped with short-range high-speed missiles will loiter near the expected target exposure sites.
- The distance to the target is greater than the distance currently allowed by treaty (> 600 km) for surface-launched ballistic missiles. Aircraft will act as a set of booster legs when remote targets must be attacked.
- The pilot must detect the target visually, and his judgment is essential for critical weapon-release decisions.

The panel foresees that cruise missiles will be retained in the operational inventory for much if not all of the period of 25 to 35 years considered by this study. Efforts will be made to extend their range and improve their survivability. Ultimately they will be displaced largely by precision-guided rockets. The range

of cruise missiles designed for use against static targets will be determined by the energetics and the volume of the propulsive fuels they carry and by aerodynamic design factors (lift-to-drag ratio, payload weight, and the like). Although significantly more energetic fuels are possible, the panel believes that the introduction of such fuels into operational weapon systems will, for reasons of operational safety, environmental handling problems, and cost, proceed slowly.

ANALYSIS OF DURATION AND COSTS FOR FUTURE NAVY AND MARINE CORPS FORCE-PROJECTION MISSIONS

The global proliferation of theater ballistic missiles (TBMs), cruise missiles (CMs), and weapons of mass destruction (WMD) is likely to continue for many decades and could seriously affect the ability of the United States, and particularly the Navy and Marine Corps, to project military forces in regions of significant importance to the United States. The trend toward hardening and burying critical military sites will make it more difficult and costly for U.S. projection forces to suppress an enemy's ability to launch TBMs and employ WMD. The following analysis is meant to explore the potential impact of these emerging threats on future Navy and Marine Corps tactics, weapons, and weapons platforms.

The scenario employed to understand the impact of these threats and what U.S. responses to them might be assumed that, near the outset of a conflict, an attack by U.S. Navy and Marine Corps forces on 500 critical enemy targets, both fixed and mobile, both hardened and soft, is required. The objective for the U.S. forces was to destroy 75 percent of these targets as rapidly as possible. The assessment assumes that the surface components of the U.S. naval fleet are standing offshore either 50 km or 400 km and that the arsenal submarine is always standing 50 km offshore. The standoff range is dictated by the threat perceived for inshore operations, whether from cruise missiles, submarines, or TBMs. The cost for destroying 75 percent of the targets was estimated for three different naval platforms to deliver precision-guided ordnance by aircraft on aircraft carriers, by arsenal ships, and by arsenal submarines.

In the analysis, the following assumptions are made:

1. Carrier-based aircraft have an operational range of 500 kilometers.
2. For the 50-km standoff case, arsenal ships, arsenal submarines, and aircraft carriers are all employed. The arsenal ship and the arsenal submarine have a mix of 150- and 500-km precision-guided missiles (PGMs).
3. For the 500-km standoff case, arsenal ships and aircraft carriers are employed, and the arsenal ship carries only 500-km PGMs.
4. The arsenal ship and the aircraft carrier require defense against TBMs when they are stationed 50 km offshore, but not when they are stationed 400 km offshore. The arsenal submarine is presumed to be untargetable by TBMs.

5. Enemy high-altitude air defenses have been suppressed by prior missile attacks, and carrier aircraft can operate above 15,000 feet with a loss rate of 0.001 per sortie.

6. Sortie rates for carrier aircraft are reduced by a factor of 2 when the carrier is stationed 400 km offshore.

7. This analysis does not include cost of carrier or arsenal ship attrition given the failure of the TMD system.

The analysis presented here is overly simplistic and attempts to identify only the effect of ship standoff distances. In a complete comparison of nuclear-powered aircraft carriers (CVNs) versus arsenal ships and submarines, one needs to add in not only the cost per day of operation but also training and ship procurement costs. These are not included in this model, and if applied, they give a great sensitivity to the duration of conflict and the number of aim points (targets) per conflict. If the number of aim points is relatively small, such as the 500 assumed in this illustrative calculation, the computation has illustrative validity. If, on the other hand, the number of aim points approached 50,000, both the choice of weapons and the delivery system would be different.

It is worth commenting that START I (Article V.1B(a)) limits the range of ballistic missiles on surface ships to less than 600 km, but there is no range limit for submarine-launched ballistic missiles (SLBMs). (See Appendix B.)

The specific offense-defense parameters and assumptions employed in this assessment are shown in Table 3.1. The results of this analysis are shown in Tables 3.2 and 3.3. The difference between Tables 3.1 and 3.2 is the assumed daily costs to maintain a given level of operations in the theater. Table 3.2 assumed a smaller conflict with a \$25 million per day operational cost (not including weapons), and Table 3.3, a larger conflict with a \$50 million per day cost. U.S. operational costs were estimated to be in the neighborhood of \$75 million per day. Where a 50-km standoff distance was safe, the cost to destroy 75 percent of the targets was least for the carrier-based aircraft using the less costly precision-guided bombs (PGBs) to attack the targets, even though it took five times longer to accomplish, 10 days instead of the 2 needed for the arsenal ship and arsenal submarine.

If the surface vessels have to commit some of their weapons to self-defense, as the price for operating 50 km offshore as contrasted with 400 km offshore, their cost of combat increases. As an example, we treat the case of a modest TBM threat. For the smaller \$25 million-a-day war, the aircraft carrier force remains reasonably competitive in cost compared with the arsenal submarines if an effective TMD is available, i.e., the number of attacking warheads the Navy's TMD is designed to defend against and the number of interceptors deployed is limited. For example, 60 deployed interceptors, with a 0.75 probability of intercept, can keep all 20 attacking TBM unitary warheads from penetrating with a probability of 0.75. This criterion is an arbitrary one and is equivalent to keeping

TABLE 3.1 Parameters and Assumptions Used in Assessing Force Projection

U.S. Performance Parameters	Enemy Parameters
Offense Cost/PGB: \$75,000 (Cost per aircraft: \$50M) Cost/150-km TBM: \$250,000 (Cost per sortie: \$10,000) Cost/500-km TBM: \$500,000 (Probability of target hit: 0.5) Sortie rate (50-km standoff): 75 per day Sortie rate (400-km standoff): 37.5 per day Aircraft attrition rate (> 15,000 ft altitude): 0.001 Daily operational costs of conflict: \$25M to \$50M Minimum operational days: 2	Number of hard targets (2 hits per target required): 250 Number of soft targets (1 hit per target required): 250 Number of counterattacking TBM with unitary warhead: 20 to 40 Maximum TBM range: 500 kilometers Probability of target hit: 1.0
Defense Probability of intercept: 0.5, 0.75 Probability of penetration: 0.75 Cost per intercept: \$2M Intercept doctrine: Shoot-look-salvo (independent trials)	

TABLE 3.2 Comparison of Mission Duration and Cost vs. Offshore Standoff Range (Smaller Conflict: $\$25 \times 10^6$ cost per day)

		No TBM Threat 50-km Standoff	TBM Threat 50-km Standoff	TBM Threat 50-km Standoff	No TBM Threat 400-km Standoff
		No TMD[a]	TMD, Pi =.5	TMD, Pi =.75	No TMD
CVN[b] (1,500 PGB)	Cost $\$ \times 10^6$ Duration	\$400 10 days	\$650 to \$1,000[c] 10 days	\$505 to \$700[c] 10 days	\$700 20 days
Arsenal Ships (1,500 PGM)	Cost $\$ \times 10^6$ Duration	\$600 2 days	\$850 to \$1,170[c] 2 days	\$725 to \$875[c] 2 days	\$850 2 days
Arsenal Submarines (1,500 PGM)	Cost $\$ \times 10^6$ Duration	\$600 2 days	\$600 2 days	\$600 2 days	N/A N/A
Onshore operations range (km)		0 to 450	0 to 450	0 to 450	0 to 100

[a]TMD = theater missile defense.
[b]CVN = nuclear-powered aircraft carrier.
[c]Deployed TMD.

TABLE 3.3 Comparison of Mission Duration and Cost vs. Offshore Standoff Range (Larger Conflict: $\$50 \times 10^6$ cost per day)

		No TBM Threat 50-km Standoff	TBM Threat 50-km Standoff	TBM Threat 50-km Standoff
		No TMD[a]	TMD, Pi =.5	TMD, Pi =.75
CVN[b] (1,500 PGB)	Cost $\$ \times 10^6$	\$650	\$900 to \$1,250[c]	\$775 to \$950[c]
	Duration	10 days	10 days	10 days
Arsenal Ships (1,500 PGM)	Cost $\$ \times 10^6$	\$650	\$900 to \$1,250[b]	\$775 to \$950[b]
	Duration	2 days	2 days	2 days
Arsenal Submarines (1,500 PGM)	Cost $\$ \times 10^6$	\$650	\$650	\$650
	Duration	2 days	2 days	2 days
Onshore operations range (km)	0 to 450	0 to 450	0 to 450	

[a]TMD = theater missile defense.
[b]CVN = nuclear-powered aircraft carrier.
[c]Deployed TMD.

larger attacks from penetrating with a smaller probability. Figure 3.1 gives the number of interceptors required as a function of the TBM attack size and interceptor capability. A doctrine of shoot-look-salvo was used to estimate the interceptor requirements.

If the aircraft carrier and arsenal ships are forced to operate 400 km offshore, their respective costs rise, making the arsenal submarine, which can operate safely at a 50-km standoff range or closer, the option of least mission cost and duration (particularly if the conflict is a relatively large one with high daily operational costs).

Certainly other parameter changes could strongly influence the results of this preliminary assessment, particularly changes in missile costs and effectiveness, number of weapons per launch tube, both for offense and defense systems, and the impact of weather and standoff range on the sortie rates for carrier-based aircraft. Moreover, the cost to develop, deploy, and operate the necessary number of arsenal ships and submarines has not been considered in this very preliminary analysis.

The total number of PGBs and PGMs needed for this mission was about 1,500, requiring about three arsenal ships operating with only one weapon per VLS cell, and possibly twice that number of arsenal submarines. If, however, the arsenal submarine can operate closer into shore, it may contain a higher average number of TBMs per VLS tube requiring fewer submarines. What is important to note is that an arsenal submarine that can survive close in may be a versatile and cost-effective platform in the future for the delivery of PGMs and, therefore, a viable candidate for the Navy to consider. It may also be proven in a more detailed analysis that a mix of aircraft carriers

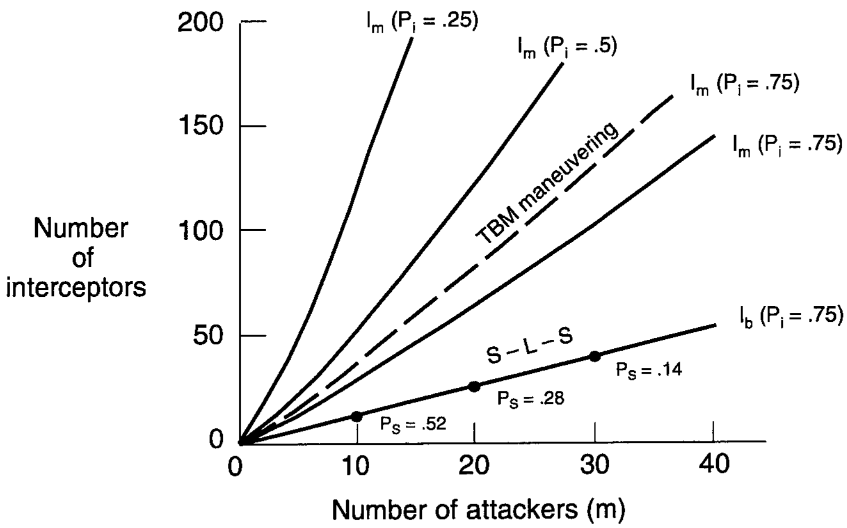


FIGURE 3.1 Number of interceptors (I) versus TBM attack size and interceptor capability. I_b, S-L-S, shoot-look-shoot (single shot); I_m, shoot-look-salvo (many shots); TBM, theater ballistic missile; P_s, probability of survival; P_i, probability of intercept.

and arsenal submarines would be most flexible and responsive for a variety of operational needs of the Navy and the Marines in the future. Moreover, the deployment of even longer-range PGMs on arsenal submarines is not prohibited by treaty. Although the deployment of TBMs with ranges greater than 600 km is not prohibited by treaty, there is some ambiguity as to whether, and under what manner of deployment, they would be counted against the START I SLBM limits, but if accurate longer-range enemy CMs or TBMs were to be a viable threat in the future, both carriers and arsenal ships might have to consider operating beyond the effective range of their weapons until that threat was eliminated, perhaps by the PGMs from an arsenal submarine.

PROJECTED EVOLUTION OF SURFACE-TO-SURFACE WEAPONS

Background

The ideal weapon for strike operations would have the attributes shown below.[1] These attributes appear to be within reach.

[1]Defense Science Board. 1996. *Summer Study Task Force on Tactics and Technology for 21st-Century Military Superiority, Volume 2, Part 1: Supporting Materials, Technology Concepts Panel Report,* p. 42.

- *Affordable cost:* \$30,000 to \$100,000 unit fly-away cost even in short 5,000-unit production runs for an economic ratio against low-cost tactical targets.
- *Rapid response:* < 2-minute response for close-ground combat support from 200-km standoff, < 10-minute response for coordinated tactically surprising strike from 1,000-km standoff.
- *Countermeasure resistance:* geodetic targeting with jam-resistant, high-grade GPS/INS.
- *Launcher compatibility:* modularly sized to fit all tactical and strategic aircraft, ground multiple-launch rocket system (MLRS), and VLS-equipped surface ships and submarines.
- *Assured lethality:* tailorable ordnance loads with hypersonic (i.e., high kinetic energy), selectable terminal approach path to cope with the full spectrum of soft to hard, point and area, stationary and moving targets.
- *Moving target accommodation:* terminal phase update by own sensor, third-party surveillance, or smart submunition ordnance load to cope with moving targets.
- *High survivability:* long standoff for sanctuary, high fast transit for enroute immunity, and stealthy, evasively maneuverable terminal phase for final defense penetration.
- *Minimal collateral damage:* < 20-m CEP in GPS-jammed environment to allow effective use of small (< 250-lb) submunition ordnance loads and to permit close approach to juxtapositioned friendly forces or politically sensitive enemy assets.
- *Surprising arrival:* distant launch and stealthy, hypersonic transit to reduce or eliminate target-reactive passive damage-limitation measures.
- *Treaty compliance:* < 600-km Intermediate Nuclear Force (INF) Treaty-limited ground launch and unambiguous shape differentiation for long standoff launch from nonstrategic aircraft.

Weapon Derivation

Competing Weapon Delivery Options

Rapid delivery of warheads to theater (500 to 1,000 km) and regional (2,000 to 3,000 km) ranges can be achieved by a variety of mechanizations, as shown in Figure 3.2 and Table 3.4. Included are rocket-propelled missiles (exorelease buses, maneuverable reentry vehicles [MaRVs], and hypersonic glide vehicles), cruise missiles (scramjet, ramjet, supersonic and subsonic turbine, and reciprocating engine propeller) and guns (pure and hybrid). These differ in cost, delivery efficiency, warhead-target tailorability, speed, countermeasure resistance, enroute and terminal-phase survivability, launch source burden, and subsystem commonality among variants. Comparison of the several competing weapon delivery schemes should consider the following issues:

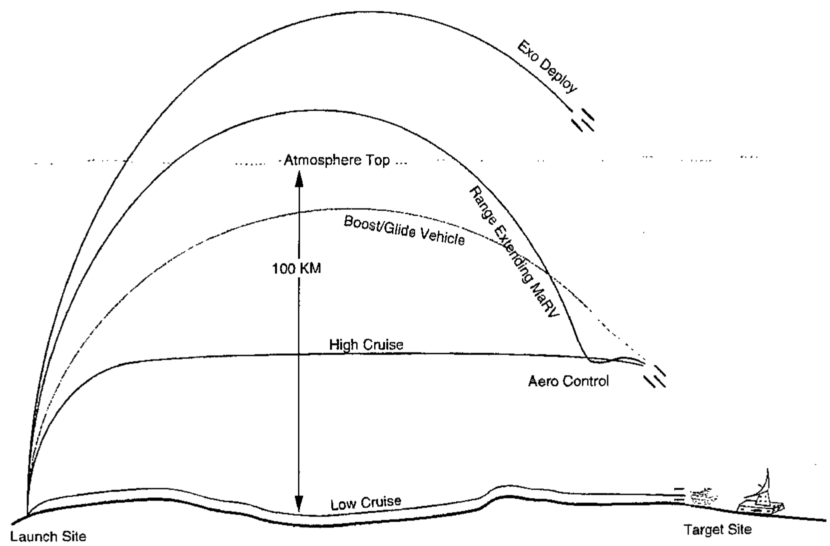


FIGURE 3.2 Low-cost, precision-attack weapon delivery options. SOURCE: Kuhn, I.R., Jr., C.D. Griffith, B.D. James, and A. Lee. 1988. *Low-Cost, Precision Attack Weapons, Final Report*, prepared for Naval Ocean Systems Center by Directed Technologies, Inc., Arlington, Va., December, p. 1-3.

- Fly-away cost, weight, and size per payload weight to reveal basic delivery efficiency at each range (theater, regional) for volume-limited, weight-limited, and dollar-limited designs.
- Warhead weight fraction per throw weight to differentiate structural and control weight penalties inherent in the various delivery vehicle airframe concepts.
- Warhead coverage efficiency against soft, hard, and mobile targets at each of the ranges to highlight the terminal phase dependence of submunition lethal agent size (weight) versus lethal pattern radius versus laydown pattern areal density (and hence, kill probability versus delivery error).
- Target mix and cost to determine the emphasis to be placed on the soft versus hard versus moving targets for warhead characterization and sizing.
- Warhead and endgame adaptation against moving targets to include circular and shaped submunition laydown patterns, dispensed guided submunitions, and terminal-phase homing.
- Submunition laydown pattern fidelity to ascertain risks of and cures for the peculiarities of the submunition dispensing and postrelease behavior for exoatmospheric and hypersonic endoatmospheric conditions.
- GPS guidance countermeasure susceptibility to measure the differential effect of jamming on impact point errors as a function of terminal approach speed, trajectory, and submunition release standoff distance.

TABLE 3.4 Competing Delivery Schemes

Short Name	Launch	Midcourse	Terminal Phase
Exorelease	Rocket	Exoballistic	Exobus (> M4 impact)
Rocket MaRV	Rocket	Exoballistic	MaRV (> M4 impact)
HGV	Rocket	Hypersonic glide	Lifting body (> M4 impact
Scramjet	Rocket boost to M4	> M6, 35-km altitude	Powered aero (> M4 impact)
Ramjet	Rocket boost to M 1.8	> M3, 25-km altitude	Powered aero (> M4 impact)
Supersonic turbine	Rocket boost to M.5[a]	> M1.5, 15-km altitude	Powered aero (> M2 impact)
Supersonic turbine	Rocket boost to M.5[a]	> M0.75, 10- to 300-m altitude	Powered aero (> M0.75 impact)
Supersonic propeller	Rocket boost to M.2[a]	M0.5 to 0.7, 10- to 30-m altitude	Powered aero (> M0.75 impact)
Hybrid gun	Gun-launched rocket	Exoballistic	MaRV (> M4 impact)
Pure gun	Gun only	Exoballistic	MaRV (> M4 impact)

[a]Air launch eliminates need for rocket booster.
SOURCE: Kuhn, I.R., Jr., C.D. Griffith, B.D. James, and A. Lee. 1988. *Low-Cost, Precision Attack Weapons, Final Report*, prepared for Naval Ocean Systems Center by Directed Technologies, Inc., Arlington, Va., December, p. 1-4.

- Alternative guidance in the absence of GPS satellites to illuminate cost or configuration penalties or trajectory-shaping requirements to cope with this adversity and to explore low-cost map matching as an alternative.
- Weapon penetration survivability to show strengths and weaknesses resulting from enroute and terminal-phase speed, altitude, observability, maneuverability, and submunition release standoff.
- Weapon time-responsiveness to quantify the benefits of rapid response (intelligence/command lag and transit speed) for such purposes as tactical surprise; timely SAM suppression in concert with air strikes; timely close support of ground combat forces; early debilitation of airfields, terminals, choke points, rail lines, and so on; inventory-conserving shoot-look-shoot cycle; minimizing exposure of forward-observing assets; and limiting target positional uncertainty of portable or mobile targets.
- Launcher compatibility to recognize ground, sea, and air backfit and loadout constraints.
- Low production and support costs to assure that large numbers of low-value targets ($50,000) can be attacked economically, using high-rate, ordnance-grade manufacturing techniques and weapon subsystem commonality.
- Treaty implications to assure compliance with launch source, range, and transit mode constraints.

Several of these issues are treated qualitatively in Table 3.5 to try to illustrate the pronounced performance difference among the various delivery schemes with

TABLE 3.5 Evaluation of 500-km Precision-attack Weapon Options

	Payload Delivery Cost	Response Time (min)	Enroute and Terminal Survivability	Counter-measure Resistance	Warhead-Trajectory Tailorability	Launcher Restrictions
Ex–Ballistic	$$$	7 ($$$)	$$$	$$$	$	$$$
Rocket/MaRV	$$$	7 ($$$)	$$$	$$$	$$$	$$$
Gun/MaRV	$$	7 ($$$)	$$$	$$$	$$	$
Boost Glide	$$	8 ($$$)	$$$	$$$	$$$	$$$
Scramjet (>M6)	$$$/$$	5 ($$$)	$$$	$$$	$$$	$$$
Ramjet (>M3)	$$$/$$	10 ($$)	$$$	$$	$$	$$$
Supersonic Turb. (>M2)	$$$/$$	14 ($$)	$$	$$	$$	$$$
Subsonic Turb. (>M0.8)	$$$	36 ($)	$	$	$	$$$
Recip. Prop. (M0.6)	$$$	48 ($)	$	$	$	$$$

NOTE: The symbol $$$ indicates high cost, $$ indicates moderate cost, and $ indicates low cost.

respect to the operational variables of interest, namely, fly-away cost per kill, kill response time, survivability/CM resistance, tailorability of warhead, and launcher restrictions. By the reasoning displayed in the figures and tables, the rocket/MaRV appears to be inherently superior to other means.

As is well understood, the United States is not infinitely wealthy, and in a very real sense, there is an economic limit on the amount that this country can spend on a given campaign. The price of weapons that can be used is related to both the value of the targets being destroyed and the anticipated number of targets that need to be destroyed. For any individual target, it is neither necessary nor sufficient for the United States to spend less to destroy the target than it cost to produce the target. First of all, there are the cost incurred by the opponent in getting the target to the area of operations and the saliency of the target both to the United States and to our opponent. But most important is the relative wealth of the United States and the opponent. Ultimately the issue faced by any proponent of a weapon system is whether the United States as a nation, using a proposed weapon and weapon delivery system, can afford (or have a military need) to destroy the entire number of targets possessed by the opponent.

Some Point Design Considerations

Four conventional attack weapon design variants, shown in Figure 3.3, have been configured to meet the performance requirements specified above, two theater and two regional, differing mainly in launch source and range.

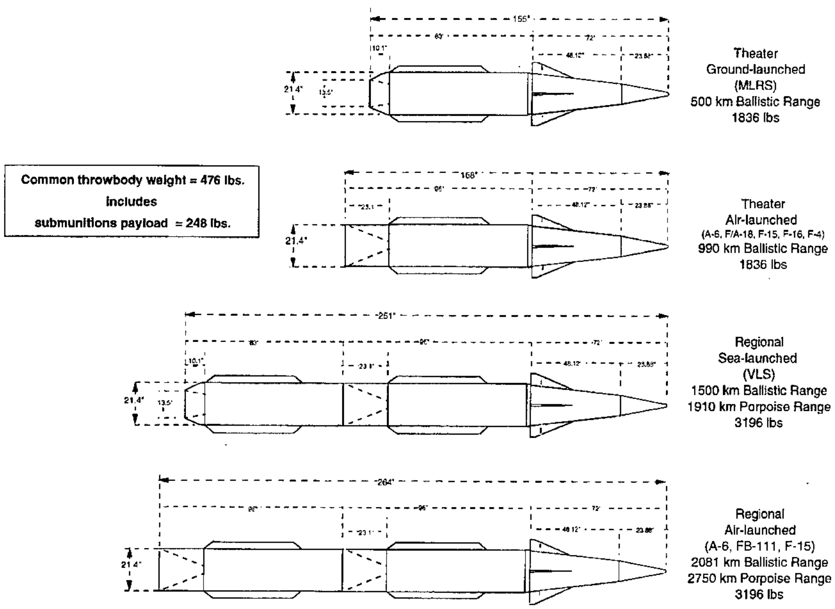


FIGURE 3.3 Conventional attack weapon variants. SOURCE: Kuhn, I.R., Jr., C.D. Griffith, B.D. James, and A. Lee. 1988. *Low-Cost, Precision Attack Weapons, Final Report*, prepared for Naval Ocean Systems Center by Directed Technologies, Inc., Arlington, Va., December, pp. 1-6 and 3-2.

All of the weapons are assumed to carry a common 476-lb, 72-in. biconic throwbody containing 248 lb of submunitions, mounted on a booster or combination of boosters depending on the mission. The two theater variants are boosted by a single stage whereas the regional variants require two stages.

There are two basic booster units, differing only in the nozzle configurations. The solid rocket case itself is a cylinder 72.9 inches long with a diameter of 21.4 inches for both booster configurations. The nozzle for a booster stage firing at sea level (i.e., either the ground-launched theater weapon booster or the first stage of the sea-launched regional weapon) is designed to have an expansion ratio of 7 to 1, is 10.1-in. long, and has an exit diameter of 13.5 inches. This booster is estimated to achieve a delivered specific impulse of 253 seconds. Alternatively, the nozzle for a booster firing at altitude (i.e., air-launched variants and the second stage of the sea-launched regional weapon) has an expansion ratio of 30 to 1, a length of 23.1 inches, and an exit diameter of 21.4 inches. This booster achieves a delivered specific impulse of 280 seconds. All stages have nominal 27-second burn times.

The MaRV throwbody is displayed in Figure 3.4 with a representative ordnance load of 250 lb (539 Mark 77 submunitions). GPS-receive antennas are mounted on the upper two sides and rear.

CONVENTIONAL THEATER MARV WEIGHT BREAKDOWN

	lbs.	lbs.
Ordnance		250
Submunitions (539 Mk.77 grenades	248	
Blow-off gas generator and skin cutter	2	
Airframe		152
Titanium nose tip	8	
Carbon phenolic skin/heat shield	80	
Munition mount & internal structure	38	
Stabilizer (4)	16	
Rudder (4)	10	
Guidance & Control		44
Battery	10	
Power conditioning & distribution	10	
Control surface actuators (4)	14	
Flight management (GPS/IMU/FCC, antennas)	10	
Margin		30
TOTAL		476

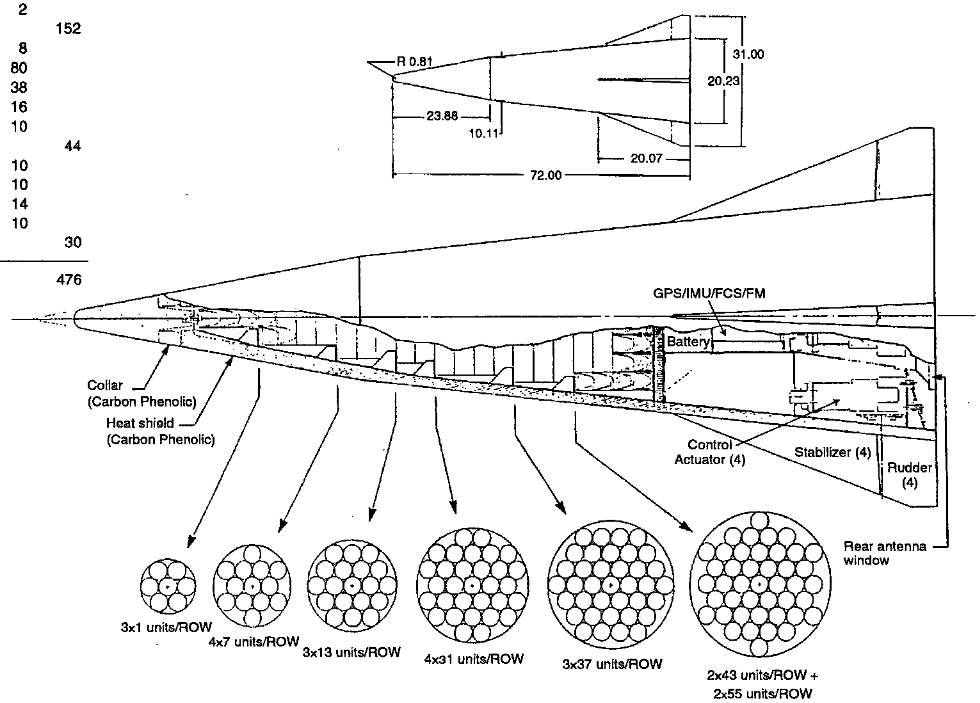
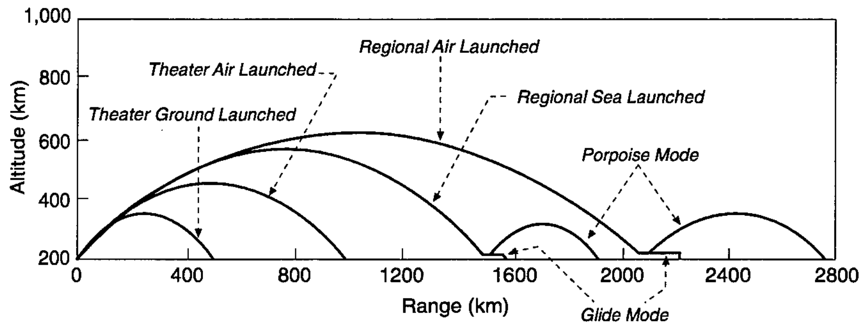


FIGURE 3.4 Representative conventional MaRV. SOURCE: Kuhn, I.R., Jr., C.D. Griffith, B.D. James, and A. Lee. 1988. *Low-Cost, Precision Attack Weapons, Final Report,* prepared for Naval Ocean Systems Center by Directed Technologies, Inc., Arlington, Va., December, pp. 1-7 and 3-25.



	Launch Source	Max Range (km)	Flight Time (min)
Theater	ground	500	6.3
	tactical air	990	8.3
Regional	sea	1910	15.9
	air	2750	18.7

FIGURE 3.5 Low-cost, precision-attack weapon trajectories. SOURCE: Kuhn, I.R., Jr., C.D. Griffith, B.D. James, and A. Lee. 1988. *Low-Cost, Precision Attack Weapons, Final Report*, prepared for Naval Ocean Systems Center by Directed Technologies, Inc., Arlington, Va., December, p. 1-8.

Figure 3.5 shows the trajectories of the four variants, including the porpoise maneuver, which converts the excess kinetic energy after reentry on the regional variants into additional range. All variants can pull high-*g* turns in terminal phase to correct for trajectory error, to evade defenses, and to tailor the target approach axis (e.g., hit the back side of mountains). Each also can deliver submunitions from a 3-km release altitude at M4.

Estimated Fly-away Cost

The cost of the precision-attack weapon must be kept low for two reasons:

- *Dollar exchange ratio.* If the number of targets that must be negated is large enough, a point will always be reached where it will become economically infeasible for the United States to attack low-value tactical targets with weapons that cost substantially more than the targets they destroy.
- *Budget affordability.* To be applied pervasively, hence to fundamentally change warfare and to displace other force modes that currently fulfill the attack function, large numbers (> 100,000 units) must be fielded.

Typical low-value targets of interest are individual parked trucks with contained equipment, armored personnel carriers (APCs), tactical command posts,

SAM antennas, artillery pieces, and the like. These soft and semisoft equipments can cost less than \$50,000 to \$100,000 each and represent a significant fraction of the total target set. Hardened targets such as tanks, aircraft shelters, and C^3/ ammo/weapon bunkers are generally much more expensive, hence are worthy of the expenditure of several low-cost attack weapons.

If the price of the attack weapon can be held down to \$100,000, then life-cycle cost of 100,000 units (fly-away, launchers, and support) can be held to \$30 billion (FY 1996), a potentially affordable amount for such a major force component. This cost target should be identified as a core goal in future Department of the Navy and DOD strike weapon development.

That this startling cost reduction may be realistically achievable is illustrated by the following breakout of cost goals for the critical subsystems. Table 3.6 displays cost goals for each of the major components, based on cost estimates from current programs. For example, DARPA GPS guidance package (GGP) program estimates a \$15,000 price (15,000 units) for a 20-m CEP worst-case jammed guidance subsystem. M77 submunitions for the MLRS were \$6.75/lb in FY 1987, leading to a \$10/lb 1996 allowance for a warhead that includes mounting structure, deployment mechanism, and submunitions. Baseline propellant was delivered in FY 1987 for < \$2/lb and the propulsion section of the MLRS was \$6.85/lb, and the fly-away MLRS missile in shipping container was approximately \$10/lb. After inflation adjustment, an allowance of \$15/lb is given to the propulsion module that benefits from economies of scale but suffers from all-carbon cases and thrust vector control.

A learning curve of 0.85 per production doubling is assumed for all subsystems except the ordnance load, which would be drawn from current high-rate manufacturing sources. It is relevant to note that, using ATACMS as a procurement baseline, eight doublings of procurement with a 0.85 learning coefficient would bring the numbers up to 100,000 procured at a unit price of \$100,000.

Warhead Tailorability

If we assume a nominal 10-m CEP GPS-guided impact distribution in a clean environment with target mapping errors less than 5 m, as would be considered reasonable today, then a weapon with a 250-lb ordnance load would be adequate for most targets provided that a jammed environment did not deteriorate the impact distribution to more than 20-m CEP. As shown in Figure 3.6, a number of different payloads can be incorporated into the MaRV throwbody.

Note first that 539 Mk 77 shaped-charge grenades (100-mm armor piercing shaped-charge and lateral antipersonnel shrapnel) with 3.4-m spacing or 9,360 flechettes (hypersonic antipersonnel) with 0.8-m spacing can be laid down in 80-m-diameter patterns (i.e., football field size) to assure 0.95 probability coverage of a severely jam-degraded 20-m CEP impact distribution. Alternatively, 100

TABLE 3.6 Low-cost, Precision-attack Weapon Cost Breakdown (1996 $)

		Total Production Run Length				
	High Rate Reference Cost	5,000 units ($/lb)	10,000 units ($K)	20,000 units ($K)	40,000 units ($K)	80,000 units ($K)
MaRV throwbody (476 lb)	52	44.6	39.0	33.1	28.5	24.5
Warhead and deployment (250 lb)	10	2.5	2.5	2.5	2.5	2.5
Aeroshell and structure	20	5.7	4.9	4.2	3.5	3.0
Control actuators (4)	500 ea	3.8	3.8	2.8	2.4	2.0
Electrical and power conditioning	200	3.8	3.3	2.8	2.4	2.0
GPS guidance package	1,500	19.2	16.4	13.9	11.8	10.0
Integration and test	10	9.6	8.1	6.9	5.9	5.0
Propulsion (1,360 lb, 1-stage, theater)	15	39.3	33.4	28.4	24.2	20.5
Propellant (1,224 lb)	4	9.4	8.0	6.8	5.8	4.9
Case, nozzle, TVC	115	29.9	25.4	21.6	18.4	15.6
Integration (1,836 lb fly-away, theater)	3	10.5	9.0	7.6	6.5	5.5
Shipping/launch container (theater)	1	3.4	2.9	2.5	2.1	1.8
Forward operating base (theater weapon)	28	97.8	84.3	71.6	61.3	52.3
Propulsion (2,720 lb, 2-stage, regional)	15	78.6	66.8	56.8	48.4	41.0
Integration (3,200 lb fly-away, regional)	3	18.4	15.6	13.3	11.3	9.6
Shipping/launch container (regional)	1	6.1	5.2	4.4	3.8	3.2
Forward operating base (regional weapon)	24	147.7	126.6	107.6	92.0	78.3

hypersonic 2.5-lb bunker penetrators could cover with 0.95 probability a 10-m CEP unjammed impact distribution.

Only the very hard structural targets such as bridges and underground facility entrances would present a problem for current 10-m CEP unjammed impact distributions because a 250-lb GP bomb (for instance) needs < 2.5 m standoff and preferably an orthogonal direct hit to take down even a 3-ft thick steel reinforced concrete abutment.

Leverage Technologies for Future Application

Below is a list of potential leverage areas for standoff weapon (SOW) improvements:

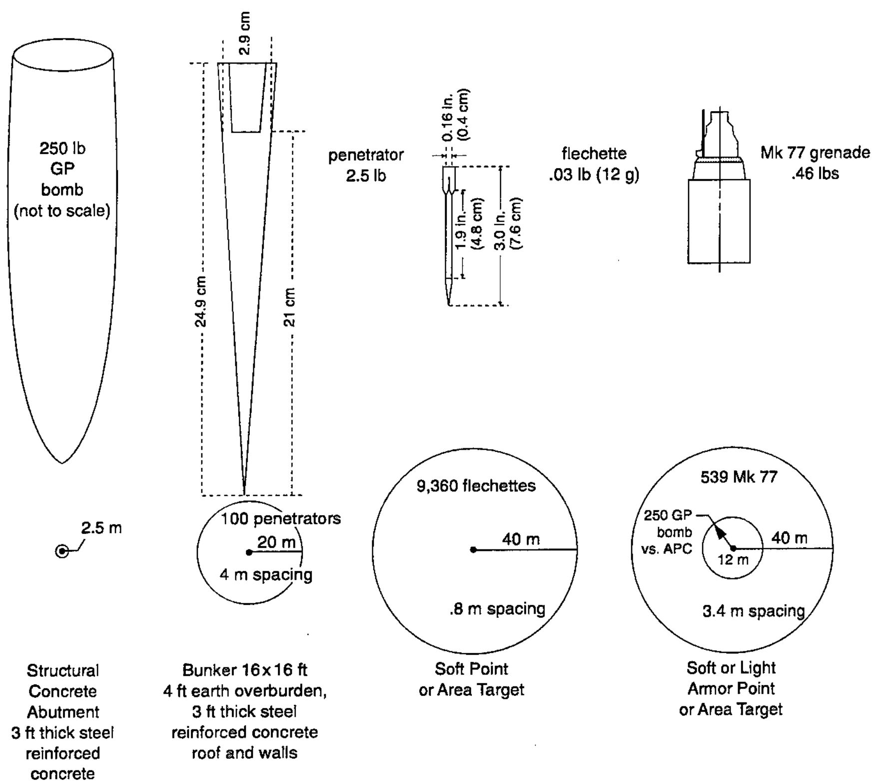


FIGURE 3.6 Alternative 250-lb ordnance laydown patterns. SOURCE: Defense Science Board. 1996. "Long Range Precision Weapons," *Summer Study Task Force on Tactics and Technology for 21st-Century Military Superiority, Volume 2, Part 1: Supporting Materials, Technology Concepts Panel Report,* Section VII, Office of the Under Secretary of Defense for Acquisition and Technology, Washington, D.C., October, p. 45.

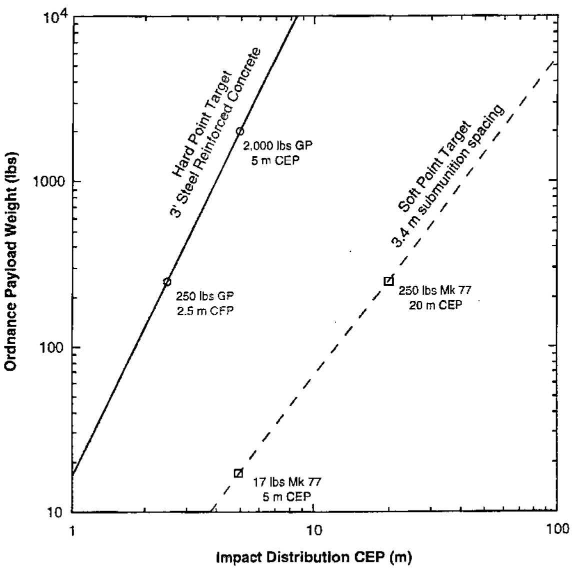
- Payload size
  - —Delivery precision
    - —Guidance accuracy
    - —Countermeasure resistance
    - —Target localization accuracy
  - —Lethal area per ordnance weight
    - —Explosive energetics
    - —Dumb submunition areal density and kinetic energy
    - —Smart submunition capture area
- Delivery efficiency
  - —Propulsion technique
  - —Fuel energetics
  - —Ordnance payload wrap factor

- Terminal phase flexibility
  —Approach path diversity
  —Impact velocity
- Transit survivability
  —Observables
  —Transit velocity and trajectory profile
  —Evasive maneuverability
- Launcher survivability and economic burden
  —Compatibility with most air, land, and sea platforms
  —Standoff range
  —Weapon weight and size
- Fly-away cost
  —Guidance
  —Propulsion
  —Production run length
  —Modularity/tailorability.

From the above list, only five areas look worthy of pursuit for big gains, since all others are mostly a matter of design. These are the three factors affecting geodetic targeting impact accuracy (namely, GPS guidance accuracy, GPS countermeasure resistance, and target localization accuracy) and the two factors influenced by improvement in chemical energetics (namely, warhead explosive yield and propellant I_{SP}). Figure 3.7 illustrates three points about guidance accuracy improvements.

- *Impact accuracy is the single highest-leverage area available for point targets.* Ordnance weight, hence throw weight, hence missile size, hence missile fly-away cost, varies approximately as the square of the required lethal pattern radius for submunitions at a given areal density, or as the cube of the standoff radius for monolithic high energy (HE).
- *Programmed or expected improvements in GPS ephemeris and receiver accuracy will reduce CEP to less than 2 m in an unjammed environment without heroic development effort.* Wide-area GPS enhancement (WAGE) programs 1, 2, and 3 improvements and normal receiver technology advances will bring about this two- to fivefold reduction.
- *The fiber-optic inertial unit in DARPA's GGP should hold jamout impact distribution deterioration to < 3 m.* GGP is expected to give 0.003°/h drift and not worse than 0.3°/h drift in a high-*g* terminal maneuver.

If, as expected, surveillance imagery from space and airborne sources and long baseline signal intelligence (SIGINT) from airborne sources can be registered to 1-m CEP accuracy in reasonably feature-rich, benchmarked geographies, then overall target localization CEP can be held to ~2 m CEP. Therefore, if high-quality antijam antennas and clocks can be incorporated with the GGP, such as to hold onto GPS lock until 20 seconds (40 km) prior



	Non-Differential GPS Unjammed	
	CEP (m)	SPE (m)
Advertised	10	16
Achieved	4.0	6.8
WAGE 1	3.2	5.6
WAGE 2	2.7	4.8
WAGE 3	2.4	4.3
Next Gen.	1.4	2.4

Impact Point Deterioration in Jammed Environment

Loss of GPS Signal		Inertial Drift	
Time to go (secs)	Distance to go (km)	1 nm/hr (m)	0.3 nm/hr (m)
20	40	10	3
40	80	20	6
60	120	30	9

FIGURE 3.7 Weapon payload versus guidance performance. SOURCE: Defense Science Board. 1996. "Weapon Payload vs. Guidance Performance," *Summer Study Task Force on Tactics and Technology for 21st-Century Military Superiority, Volume 2, Part 1: Supporting Materials, Technology Concepts Panel Report,* Section VII, Office of the Under Secretary of Defense for Acquisition and Technology, Washington, D.C., October, p. 46.

to impact, then 3-m CEP impact distribution in a jammed environment is not beyond reasonable projection.

Figure 3.7 and Figure 3.8 combine to demonstrate that improvements in high-explosive (HE) energy density (factors of 2 to 4) result in only small lethal radius improvements (factors of 1.26 to 1.59). These gains would still be markedly inferior to submunition lethality per weight against soft and armor, point, and area targets. Further, these mild factors help only slightly against deep underground and structural targets. Accuracy remains the dominant lever.

The same factors of 2 to 4 in energy density if translated into I_{SP} improvements in propellant (factors of 1.4 to 2) would give noticeable reduction in missile weight (33 to 50 percent), but not nearly that offered by foreseeable guidance improvements (see Figure 3.8).

Summary (Standoff Precision-strike Weapons)

Affordability

The panel identifies as a rational goal the development of highly target-adaptive, extremely rapid-response, maneuverable precision-guided rockets, com-

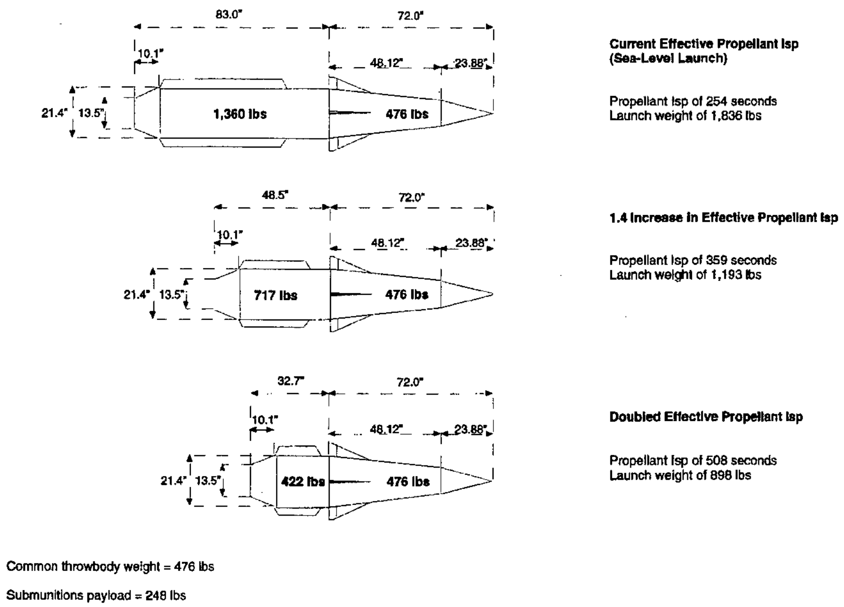


FIGURE 3.8 Impact of increasing effective propellant I_{SP} on weapon size.

TABLE 3.7 Estimated Achievable Circular Error of Probability

	Unjammed CEP (m)	Jammed CEP (m)
Current GPS with 5-m map registration, 1°/h inertial drift	10	20
WAGE 3, 1-m map registration, 0.003°/h inertial drift	< 2	< 3

pliant with all current land, sea, and air launchers and treaty compliant, provided that long production runs of >5,000 units, modular configuration, and high-grade inertial/GPS guidance are adopted. Terminal homing would not be required for most targets; if added, the cost impact will be sensitive to the success of ongoing cost reduction efforts.

Guidance Improvement Potential

The panel also believes that the largest leverage for further life-cycle cost reduction for strike of point (not area) targets will be provided by the achievement of the improved impact accuracies shown in Table 3.7 (and consequent

ordnance throw weight/missile size and weight reduction) with GPS WAGE 3 ephemeris improvements, receiver clock and antenna jam resistance, and high-grade inertial guidance (GGP).

Submunition ordnance load can be reduced to < 10 percent (25 lb) of the nominal 250 lb for a yet better areal density laydown pattern. All-up missile fly-away cost could be < $30,000, and weight could be less than 320 lb versus 3,200 lb for the 1,900- to 2,750-km surface and air-launched two-stage variant.

Energetics Improvements

Near-term chemical improvements in the I_{SP} of solid propellants are focused on improved volume energetics, not mass energetics. These would primarily affect the depth of magazine in volume-constrained situations and may be important in arsenal ships and submarines but would not adversely impact the unit cost. The greater lethality per mass of submunitions versus monolithic HE for all strike targets except deep underground and massive structures (e.g., bridges), prevents even two- to threefold improvements in HE energetics from delivering across-the-board gains in all up missile affordability or performance.

PROJECTED EVOLUTION OF AIR-TO-SURFACE WEAPONS

Background

The panel believes that the technology areas discussed in Chapter 2 will impact future air-to-surface weapon concepts and designs in much the same manner that they will impact the design of surface-to-surface weapons.

The panel seriously doubts that in the future, high-performance, high-cost naval strike aircraft will be employed on a routine basis to drop relatively inexpensive (level of effort) dumb bombs (e.g., Mk-80 series weapons) on area targets that are heavily defended. Even if the reliable suppression of enemy air defenses can be achieved, the panel does not think that the United States will ever again use its naval air power to refight the equivalent of the air campaign that was fought against North Vietnam in the 1960s and early 1970s. The panel believes that over the next 25 to 35 years, the employment of naval strike aircraft will focus progressively on situations where the following pertain:

- The pilot's capabilities for visual observation of the target and the pilot's final judgment are required.
- Rapid response is required in support of ground forces.
- A weapon platform must loiter close to the probable emergence point of an ephemeral target (e.g., pop-up artillery or Scuds).
- The range to the target exceeds the ranges for surface-launched weapons established by treaty.

Recognizing that the capability to suppress enemy air defenses may be imperfect, and recognizing the high political cost of loss and or capture of pilots, the panel believes that future air-to-surface weapons will be predominately long-range (well beyond LOS), standoff weapons.

Targeting Concepts for Standoff Air-to-surface Weapon Delivery

The section entitled "Targeting and Strike Architecture" in Chapter 2 provides some comments on the general technology for weapon targeting. For situations where the weapon launch platform is an aircraft, additional connectivity is required relative to the situation when the weapon launch platform is a ship.

In the discussion that follows, the assumption is made that if standoff air-to-surface weapon delivery is to be accomplished, then the necessary communications connectivity will be available. This connectivity may be established by the availability of a SATCOM link on the strike platform, or by LOS connections with ground observers, UAVs, or manned sensor platforms, or through an elevated relay platform such as BGPHES.

If the pilot is to release weapons from a standoff range that does not permit visual sighting of the target or high-resolution acquisition of the target by on-board sensors, then it is axiomatic that the pilot must receive targeting information from off-board sources such as the following:

- Real-time National sensor imagery,
- Processed near real-time National sensor imagery,
- Theater sensor imagery, or
- Ground observer data or imagery.

If the intention is to make maximum use of the pilot's judgment and cognitive processes for target selection and weapon allocation, then it would be desirable to transmit video imagery that can be displayed in the cockpit.

Direct connectivity with a satellite that is providing imagery is feasible if the aircraft is equipped with appropriate SATCOM capabilities. Although such direct connectivity is currently possible, it is recognized that it would be undesirable to saturate the pilot with excess imagery that cannot be analyzed in the cockpit. Future technology should permit near real-time editing of received imagery at a major control station and immediate direct retransmission to the cockpit of imagery in a pilot-friendly form.

Fortunately, not all targets are ephemeral. Many targets are relocatable but are often stationary for periods of time that are long compared with the cycle time for satellite imaging, receive location (RL) processing, and retransmission to the pilot. In addition many targets are located by electronic or signals intelligence (ELINT or SIGINT) techniques. Although the precision of target location by such means does not allow a geodetic coordinate to be selected as an aim point, the error ellipse can be sufficiently small that it falls within the acquisition basket

of a high-speed antiradiation missile (HARM). In such circumstances a weapon may be fired at an imprecisely located target with a reasonable expectation of autonomous target acquisition by the weapon.

When target data are provided by ground observers and/or by theater imagery sensors, both accurate instantaneous target coordinates and target imagery can be made available to the pilot. Depending on the weapon seekers and the availability of a data link to or from the weapon, a number of strategies are possible. If the target is not expected to move during the fly-out time of the weapon, then the pilot can fire at a geodetic coordinate.

On the other hand, if the target is moving and if updated imagery or target location information is provided continuously to the pilot, then if a data link is available to or from a sensor-equipped weapon, the pilot can provide command guidance to the weapon until it impacts the target. If weapon-to-pilot data links are not available but the target has a distinctive signature that allows a sensor on the weapon to acquire the target autonomously (e.g., in the mode of a BAT weapon), then the pilot's only problem is to fire the weapon close enough to the expected location of the target after weapon fly-out so that the weapon's sensor can acquire the target.

Simply put, the panel is persuaded that there is now a rich assortment of technologies available that will allow aircraft to attack fixed, stationary, and moving targets from safe standoff ranges. Twenty-five to 35 years in the future, the capabilities that might be presented by then-available technology should be enhanced significantly.

Air-to-Surface Weapon Costs

Four general classes of air-to-surface weapons exist, as follows:

- Unguided bombs (e.g., Mk-80 series weapons);
- Direct-attack munitions (laser or GPS/IMU-guided bombs, BAT or sensor-fused weapons, and the like);
- SOWs, which may be equipped with sensors, data links, navigational capabilities, and some means of propulsion or range extension (rocket, cruise motor, aerodynamic lift from wings or body shape, and so on); and
- Deep-strike weapons such as Tomahawk, the joint air-to-surface standoff missile (JASSM), and the tri-Service standoff attack missile (TSSAM).

Depending on the fuse or other weapon attributes, the cost of unguided bombs will be a few thousand dollars (generally less than $10,000). When released from altitudes of about 5,000 feet, such weapons generally have a probability of less than 10 percent of landing at distances that are less than the lethal radius of their warheads from the target. If released from sanctuary altitudes of above 15,000 feet, the probability of hitting the target (or at least landing within a lethal warhead radius) drops to about 1 percent or less. Because of their range of

TABLE 3.8 Approximate Cost Breakdown of Air-to-Air Weapons

Component	Percent of Weapon Cost
Seeker	40
Midcourse guidance	15
Data link	15
Autopilot	10
Airframe	5
Propulsion	10
Warhead	5

design and complexity, it is not possible to provide a single cost figure for direct-attack munitions or smart submunitions. Currently, they are likely to range in cost anywhere from about $10,000 to about $50,000. Their probability of target destruction is of course variable but may be thought of as being better than 50 percent.

Depending on the weapon's range, number and type of submunitions, propulsion system, warhead weight and complexity, data links, and sensors, SOWs can be thought of as costing between $250,000 and about $1 million. Their success rate will of course be variable and will depend on the targeting system employed and the effectiveness of the design of an individual weapon. Table 3.6 illustrates the range of costs of the various components of an air-to-surface launched standoff weapon.

For a typical tactical missile, with a data link, an approximate cost breakdown is shown in Table 3.8.

Different point designs of weapons will result in both different relative cost breakdowns and different levels of performance. The panel finds it of interest to observe that both the absolute costs of surface-to-surface missiles and air-to-air missiles and their relative percentage costs of components tend to converge when designs are normalized for equal performance, range, and payload. When such comparisons are made, surface-to-surface weapons are always more expensive for the simple reason that the price of the first-stage launch rocket does not enter into the calculation of air-to-surface weapon costs. For such weapons, the aircraft acts as a reusable first-stage booster and brings into the cost comparison the cost differentials of the ships and airframes amortized over the projected sortie life.

Such data were not available to the panel, and so no computation of true first-stage costs was performed. The panel suspects that when all costs of aircraft delivery are taken into proper account, these will not prove to be cheaper. This should hardly be surprising because the cost of the complexity and performance of any type of standoff weapon is dominated by factors other than the cost of the first-stage propulsion.

Trends in Air-to-Surface Weapon Development

There are a few strong trends in air-to-surface weapons that will have an impact on the weapon set that will be available 25 to 35 years in the future. These may be summarized as an attempt to field a small set of weapons that will be able to do the following:

- Have a standoff launch-and-leave capability,
- Be both affordable and highly effective against a wide spectrum of targets,
- Have day, night, and adverse-weather capability,
- Provide multiple kills for a single attack, and
- Have a programmable attack profile.

Since there is a significant probability that the Congress will insist that all future air-to-surface weapons will be joint, weapon developments by the Army and the Air Force will certainly affect the makeup of the future set of naval air-to-surface weapons.

The principal current or near-term Navy air-to-surface standoff weapons include or will include JASSM, JSOW, HARM, submarine-launched air missile—extended range (SLAM-ER), and TLAM. The Navy's current or near-term direct-attack air-to-surface weapons include, or will include JDAM, laser-guided bombs (LGBs), Rockeye, Walleye, Skipper, and Maverick. The Navy's current intention is to reduce the number of weapon types in its inventory.

For the near future, the Navy's principal deep-strike air-to-surface and surface-to-surface weapon will be the TLAM. JASSM is expected to be fielded by the end of the next decade.

Standoff Weapons

The prognosis for the introduction over the next 25 to 35 years of new air-to-surface weapons is unclear. The panel anticipates that in this period of time JSOW will become operational and together with HARM will constitute the Navy's principal air-to-surface weapons. SLAM and SLAM-ER should ultimately be replaced by JASSM.

Over the years, new technology can be retrofitted into both JSOW and HARM. As discussed in Chapter 2 of this report, these technologies might provide improved sensor performance, cheaper data links, better navigational accuracies, greater warhead lethality, improved aerodynamics, and greater range. In the case of HARM, its capabilities might be extended to provide new or improved capabilities to attack very high frequency (VHF) and L-band emitters, since these bands are likely to be used by counterstealth detection systems.

In a general sense, the naval forces will need a standoff air-to-surface weapon that can be configured to transport either a large unitary warhead or a large payload of submunitions. The submunitions will include future variants of BAT, sensor-

fused munitions (e.g., SFWs and SADARMs) or Mk-77 grenades (dual-purpose improved conventional munitions [DPICMs]). SLAM-ER and JASSM are potential candidates for this class of mission. The panel believes that the Navy and other Services should push for the development of a workhorse standoff air-to-surface submunition transport weapon, which is based on modifications of either SLAM-ER, JASSM, TSSAM, or an entirely new weapon airframe design.

Direct-attack Munitions for Fixed- and Rotary-wing Aircraft

The Department of the Navy's current weapon neckdown strategy calls for the replacement of its LGBs with JDAM, which is a GPS/IMU-guided weapon. With the presently programmed JDAM IMU, the weapon provides a 13-meter CEP. When GPS is denied, the CEP grows to 30 meters with the current IMU. Because many targets in the JDAM target set require a 3-meter CEP for a single-shot target kill, there is reason for concern about this projected weapon performance.

The panel believes that the naval forces have some unique requirements for a 3-meter CEP weapon. The rather modest expected JDAM performance is the result of the use of a low-performance IMU and limitations of the current GPS system. Superior IMUs are available now, and all evidence indicates that much superior IMU technology will evolve in the future. As discussed elsewhere in this report, GPS improvement programs are under way (WAGE 1 and WAGE 2) that should result in GPS accuracies of 1 to 3 meters.

The IMU unit used in JDAM was a compromise between available IMU technology and IMU cost at the time of the design freeze of JDAM. IMUs that have significantly better performance than the JDAM IMU exist now. The problem is that their unit price is high relative to the total price of JDAM. Certainly the prognosis for much improved IMU performance is extremely good. The main issue will be the unit price of such high-performance IMUs. DARPA is presently engaged in an effort to develop a low-cost, high-performance IMU.

The panel suspects that over its projected service life the performance of JDAM will improve, through a series of upgrades, to the point where JDAM will eventually become a 3-meter CEP weapon. These upgrades will occur as a result of already programmed improvements in GPS performance and through a reduction in the price of a high-performance IMU that will permit the introduction of IMUs with significantly improved performance into the JDAM configuration.

Direct attack by rotary-wing aircraft presents some unique problems and areas of concern. Currently, the Marine Corps AH-1W does not have a self-designation capability for its semiactive laser Hellfire missiles, and it is just now getting a FLIR for night operations. The Army's AH-64 (which has had a FLIR and self-designation laser capability since its introduction in the 1970s) will soon be getting the Long Bow Hellfire (with a MMW seeker) and may also later get an imaging infrared (IIR) Hellfire missile. Both of these missile systems would give Marine Corps attack helicopters a launch-and-leave capability that is important

for survivability. The panel believes that the Marine Corps should be strongly encouraged to take advantage of Army helicopter weapons and targeting systems.

With regard to weapons that are appropriate for use on rotary-wing aircraft, an alternate approach to the problem of developing a robust direct-attack munition (DAM) is being undertaken by the Army. The Army Combined Arms Weapon System (TACAWS) is intended to be a multimission weapon designed for use in air-to-air, air-to-surface, surface-to-air, and surface-to-surface modes. In the air-to-surface mode, it may be launched from both fixed- and rotary-wing aircraft.

The key enabling technologies for this weapon are its 512 × 512 indium antimonide (InSb) focal plane array that provides high resolution and a large FOV. In addition it has a quick cooldown miniature Dewar which results in rapid cooldown and a compact seeker. Finally it has a fiber-optics gyro characterized by high stability, bandwidth, precision, and reliability.

The panel believes that the rather remarkable technology that is incorporated into the 6-in.-diameter TACAWS seeker can and will be incorporated into the seekers of many future direct-attack weapons, once the cost of the included components has been reduced.

Summary (Air-to-Surface Weapons)

Since few weapon developments are under way by any of the Services, the rate of introduction of new weapons into the inventory over the next 25 to 35 years will be slow. Based on current trends in weapon development, the panel believes that over that period of time, efforts will be made to introduce technologies that will upgrade individual components of the few residual classes of weapons that will remain in service. Many of the changes that the panel suggests in "Projected Evolution of Surface-to-Surface Weapons" above in this chapter will of course be applicable to the design of future air-to-surface standoff weapons.

The panel suggests the following:

- The Department of the Navy should proceed with its present weapon "neck-down" strategy to reduce the number of weapon types in its inventory.
- The Navy and other Services should consider the evolution of a long-range standoff weapon that can serve as an effective and affordable submunition transporter.
- Improved IMUs should be retrofitted into the JDAM design so that eventually it can evolve into an affordable DAM with a 1- to 3-meter CEP.
- Both the Navy and the Marine Corps should track the Army's TACAWS sensor development and consider applications of these technologies into future close support and close combat weapons. These developments appear to be particularly appropriate for weapons designed for launch by rotary wing aircraft.

Above and beyond these specific recommendations, the panel believes that as opportunity presents itself, over the next 25 to 35 years, the naval forces should

continue to upgrade its existing weapons by refining and retrofitting new technologies that are already available in the areas listed below:

- Navigation,
- Guidance and control processors,
- Sensors,
- Propulsion,
- Data links,
- Warheads, and
- Aerodynamic performance.

WEAPONS TO SUPPORT ENGAGED FORCES ASHORE

Weapons are only one component of the overall capabilities needed to ensure the success of engaged forces ashore. The Marine Corps believes that it is imperative that its forces have superior capabilities in maneuver, firepower, command and control, combat service support, and training and education. Other panels of this study have dealt with the issues of platforms for enhanced maneuver capabilities,[2] combat service support,[3] and training and education[4] as well as the issues related to command and control.[5] Related issues are discussed in *Volume 1: Overview* and in a 1996 Naval Studies Board report, *The Navy and Marine Corps in Regional Conflict in the 21st Century.*[6] Of all of the Marine Corps major concerns, firepower and command and control are most closely intertwined.

The most far-reaching new combat concept that has been proposed for support of engaged Marine Corps forces ashore is the concept that supporting fires will come predominantly from standoff air and surface ships. In this concept, where direct-attack air-to-surface weapons are used, in the early years considered by this study, the delivery platforms will be variants of current platforms. The implementation of such concepts will certainly require the development of new weapon control doctrine, the availability of much more sophisticated command and control systems, and more robust broader bandwidth connectivity than is

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[2]Naval Studies Board. 1997. *Volume 6: Platforms, Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st-Century Force,* National Academy Press, Washington, D.C.

[3]Naval Studies Board. 1997. *Volume 8: Logistics, Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st-Century Force,* National Academy Press, Washington, D.C.

[4]Naval Studies Board. 1997. *Volume 4: Human Resources, Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st-Century Force,* National Academy Press, Washington, D.C.

[5]Naval Studies Board. 1997. *Volume 3: Information in Warfare, Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st-Century Force,* National Academy Press, Washington, D.C.

[6]Naval Studies Board. 1996. *The Navy and Marine Corps in Regional Conflict in the 21st Century,* National Academy Press, Washington, D.C.

currently available to engaged Marine Corps forces. The panel believes (more properly—assumes) that because of their centrality to evolving Marine Corps doctrine, such capabilities will become operational within the next 25 to 35 years.

A major impact of the development of improved sea-based firepower is foreseen in the area of the combat weapons that will be organic to future amphibious landing forces. Because of the sea-based firepower that the panel believes will be available, on call, to engaged forces ashore, their organic assets such as tanks and artillery will show a reduction in the logistic support required.

The combat power of a landing force is directly related to the organic fire support it owns and its access to supporting arms. The distribution of these supporting arms assets has been established by decades of experience and is firmly ensconced in Marine Corps doctrine. The introduction of significant changes into this ingrained system will take many years. Convincingly thorough demonstrations of reliable performance will be required before doctrine and commanders' philosophies will change.

Today the lowest command that holds its own organic supporting arms is the rifle company. In addition to the three infantry platoons, the Marine Corps company commander has a weapons platoon. The weapons platoon contains its assault sections, antiarmor teams, and machine gun sections and, depending on the year, the table of organization and manning level of between six and twelve 60-mm mortars. The 60-mm mortars are the company commander's personal artillery and can be used without asking permission or making requests through a cumbersome command chain over less-than-reliable communications channels. Properly trained and well led, the 200-person rifle company is a potent force.

A Marine Corps battalion commander has more organic firepower in his 800-person infantry unit. His weapons company has heavier machine guns, more potent antiarmor weapons, and an 81-mm mortar platoon. Additionally the battalion is the first level of combined arms that deploys as a true sustainable combat unit.

When a 2,000-person Marine Corps expeditionary unit (MEU) is deployed, it may be augmented with tanks and 155-mm artillery plus a composite helicopter/AV-8B squadron. Three of these MEUs are deployed around the world continually aboard amphibious ready groups (ARGs). These naval units and their associated carrier battle groups (CVBGs) constitute this nation's forward presence for friends and enemies alike to observe.

When a serious threat begins to develop, the Marine Expeditionary Force (MEF) can deploy aboard an amphibious task force of 12 to 15 amphibious ships (approximately half this nation's total assault lift capability). As each of these larger combat combined arms formations deploys, it adds tanks, artillery, light-armored vehicles, air defense, and combat service support.

The panel believes that a major decision point has been reached with regard to amphibious forces. The survivability of the huge logistic depots needed to support amphibious forces may no longer be viable. They constitute extremely lucrative targets for TBM attack with WMD or large conventional warheads. The

massive need for ammunition, fuel, and spare parts is not logistically supportable across a contested beach. Finally a determined enemy with antiship missiles, diesel submarines, and modern anti-invasion mines could create an early disaster and unacceptable casualty levels.

The panel is convinced that out of necessity, a new concept for amphibious warfare must be evolved, built, and tested as soon as possible. The Marine Corps is currently espousing the doctrine of Operational Maneuver From the Sea (OMFTS). Under this doctrine, amphibious forces will make maximum use of sea-based fire support (both air and surface fire support), and sea-based logistics to reduce or eliminate the logistics over the beach, targetable footprint, and minefield breaching problems.

In other sections of this report, various possibilities for standoff precision-guided ballistic missiles (air or surface launched) are discussed. The key to their use in support of engaged forces is the need for mechanisms to control their use by forward observers or by the commanders of the engaged force. Target designation systems that allow weapons to be launched at a geodetic coordinate will come into operational use. In addition, a variety of weapon control systems such as those discussed in the section on targeting and strike architecture should come into use that will allow a forward observer to guide an in-flight weapon to the target he is looking at. (This capability should be achievable as a result of sending a real-time camcorder type image to an inflight weapon that then does a scene correlation with the image it detects with its sensors and homes on the designated target.)

The concept appears to be straightforward and logical. However, it will require time, investment, and the convincing of many skeptics before infantry units will deploy with all of their support over the horizon (OTH) at the end of a long electronic tether.

The panel believes that heavy artillery weapons and 72-ton tanks will be progressively deemphasized and eventually eliminated by the U.S. Marine Corps because their logistics tails will not be supportable. However, until there have been numerous demonstrations of reliable, long-range, precision fires from OTH, in all-weather (day and night) conditions, landing force commanders will be reluctant to leave behind their burdensome but effective organic assets.

Sea-based firepower is the key to the reduction of the logistic tail of engaged forces ashore. If, as the panel believes possible, the commander of an engaged company or battalion can call for, and immediately receive, sufficient and appropriate fire support to allow him to accomplish his mission, there will be little justification for tanks and organic artillery in the landing force. To satisfy this requirement, the Navy must provide the landing forces with the equivalent of arsenal ships that have the necessary depth of magazine and rate of fire to satisfy the needs of the engaged combat commander.

In addition to the promise of sea-based firepower, some systems can be used at the company or battalion level that can add and make a significant difference in combat.

The 120-mm heavy mortar is readily available worldwide and is found in almost all armies except that of the United States. The reasons appear to be cultural. Artillery men do not like the mortar because it is not a true gun and infantrymen do not like it because it is another piece of machinery to transport and maintain. (As recently as the Korean War, the 4.2-in. heavy mortar was a regimental infantry weapon.) The heavy mortar has some strong points. It weighs less than 25 percent the weight of a 155-mm cannon. It can be vehicle mounted on the light-armored vehicle (LAV). It has a respectable range. Guided projectiles have been considered for years but never produced except by the United Kingdom and Sweden. Smart rounds could reduce the "level-of-effort" logistics tail by at least one order of magnitude.

The extended-range fiber-optic guided missile (ER-FOG-M) is a weapon system that will provide currently unavailable capabilities to a landing force commander. In effect the weapon is a lethal reconnaissance system. Although the FOV of the ER-FOG-M may be limited, the weapon provides a man-in-the-loop capability that allows the weapon to be guided to a remote target over the horizon. The missile-seeker and fiber-optic technology is well in hand and may help the landing force commander wean himself from 15-ton artillery pieces.

The Marine Corps will continue to field improved individual or small unit weapons. Improved versions of weapons such as the short-range antiarmor weapon (SRAW) and the shoulder-launched multipurpose assault weapon (SMAW) should be in the inventory for most if not all of the next 25 to 35 years.

The panel also believes that in the period covered by this study, an advanced system for air defense (ASAD) will become operational. ASAD will provide a passive capability for target acquisition, classification, and identification through use of integrated ESM and passive acoustic and IR sensors. ASAD will be integrated with Stinger teams who will be equipped with substantially improved versions of the currently fielded weapon.

The panel also foresees the introduction of an advanced lightweight ground weapon (ALGW) that will provide Marine Corps infantry forces with a weapon system with increased range, lethality, and accuracy. Other individual combat weapons will be developed that will provide for a new weapon that can fire both airburst and kinetic-energy projectiles. Fire control will be provided with a modular integrated sight, a laser range finder, a weapon trajectory computer, and add-on thermal and other sensors as appropriate.

GUNS (RAPIDLY RELOADABLE LAUNCH SYSTEMS FOR SMALL-DIAMETER GUIDED MISSILES/PROJECTILES)

Background

The U.S. Marine Corps has established the range requirements for naval surface fire support at a threshold value of 41 nautical miles (about 76 km) and a

goal of 63 nautical miles (about 117 km). The Navy is currently developing a forward-fit 5-in./62 gun firing an ERGM to meet these range requirements. The payload weight of the baseline ERGM, which is a rocket-assisted projectile (RAP), is 32 lb (14.54 kg) and the in-gun weight is 98 lb (44.54 kg). An advanced solid propellant is used to launch ERGM at a muzzle velocity of 2,950 fps (899 m/s) with a muzzle energy of about 18 megajoules. The initial payload design will be as a submunition cargo round with GPS/INS guidance. For armored targets, an HE round with terminal guidance is a possibility. The round diameter and weight prohibit SADARM or BAT variants. This forward-fit 5-in./62 and ERGM combination is intended for new ship construction. However, the ERGM round can be fired from slightly modified existing 5-in./54 guns (10 megajoules) but at a reduced range because of a lower muzzle velocity and because the round was optimized for the 5-in./62. For example, the baseline round, optimized for the 5-in./62 (18 megajoules), has a range of 65 nautical miles (120.6 km). When this same round is fired from the 5-in./54, the range is about 45 nautical miles (83.48 km). If the ERGM were optimized for the 5-in./54, its range would be approximately 56 nautical miles (103.9 km). These ranges are for rounds that have steel rocket motor cases. If composites were used, the resultant ranges would all increase by about 20 nautical miles (37.1 km) or, alternatively, the payload weight would increase for the same ranges.

Before the potential impact of advanced gun concepts is considered, it is well to understand some of the restraints that naval guns operate under. A conventional powder gun like the 5-in./54 launches a 70-lb (31.8 kg) projectile at 2,650 fps (808 m/s), which is equivalent to a muzzle energy of 10 megajoules. The chamber experiences a peak pressure of 52,000 psi and the adiabatic flame temperature of NACO, the standard Navy propellant in service use, is 2,232 K. These operating conditions limit the service life of the gun tube because of fatigue and erosion to about 7,000 to 10,000 rounds. The muzzle exit pressure is limited to 15,000 psi or lower so that topside equipment and personnel are not subjected to excessive blast pressures (10 to 15 psi for equipment and 1 to 2 psi for personnel). The projectile experiences *g* forces of the order of 15,000 for several milliseconds. NACO propellant has a density of 0.98 and an energy of 3.1 megajoules/liter. Thus, the 20.25-lb (9.2 kg) propellant charge for the 5-in./54 has a total energy of about 29 megajoules. The ballistic efficiency (muzzle energy/total chemical energy) is about 35 percent, and the piezometric efficiency (average pressure/peak pressure) is approximately 38 percent.

For most fire-support missions, the important parameters are accuracy of both warhead placement and target location, warhead lethality, range, and responsiveness. Muzzle velocity is important in that it provides increased range and decreases the time of flight of the projectile to the target. The intent of advanced gun developers is to achieve as high a muzzle velocity and payload as possible to gain the longest range and greatest lethality and to minimize the response time to "calls for fire." For any gun system, the controlling equation for

velocity is $V = (2*PAL/M)^{1/2}$ where V = muzzle velocity, P = average base of projectile pressure, A = area of the bore, L = the length of travel in the gun, and M = the mass of the projectile. In principle the muzzle velocity will increase by increasing P, A, L, and/or decreasing M. However, these changes are not independent, for example, increasing the length of travel by a factor of 2 will result in a velocity increase of about 10 percent, and not 41 percent as predicted from the equation because the average base of projectile pressure decreases as the length increases unless adjustments are made in the powder charge.

For a given gun/projectile system, increased muzzle velocity is achieved by increasing the average base of projectile pressure. The approach to this has resulted in a number of development programs using solid propellants, liquid propellants, and various concepts for electric guns. In the following paragraphs, a discussion of each of these approaches is provided. The panel has elected not to discuss the light gas gun, which holds the record for high velocity with experimental low-mass aerodynamic models, because of its problems with weaponization.

Solid Propellants

Attempts to increase the projectile base pressure with solid propellants have concentrated on the development of new propellants and going to higher powder loading densities in the gun chamber. Elementary analysis[7] of the hot compressed gas in a gun assuming a perfect gas with constant specific heats and no heat loss demonstrates that the impetus of the propellant is a useful figure of merit. Impetus is defined as RT/M where R is the universal gas constant and T and M are the pre-expansion gas temperature and molecular weight, respectively. In general, the development effort has concentrated on increasing the flame temperature by using additives, such as aluminum and RDX, that enhance the impetus of the propellant. The EX97 propellant being developed for the 5-in./62 has an impetus of 4,878,000 lbf/lbm[8] (1,214 J/g) compared with 3,250,000 lbf/lbm (809 J/g) for NACO, a 50 percent increase. Also the 5-in./62 will be operated at a higher peak pressure than the 5-in./54. These changes increase the muzzle velocity at the price of reduced service life.

The other approach with solids is to increase the loading density by going to more dense propellants and increasing the charge to mass ratio. There are again limits to both of these approaches, since increased density generally means increased molecular weight, and when the charge to mass ratio becomes too large, it is difficult to ignite the entire charge with conventional primers and some of the propellant is ejected unburnt from the muzzle.

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[7]Freedman, Eli. 1988. "Thermodynamic Properties of Military Gun Propellants," Chapter 5, *Gun Propulsion Technology, Vol. 109, Progress in Astronautics and Aeronautics,* Ludwig Stiefel, ed., American Institute for Astronautics and Aeronautics, Washington, D.C.

[8]Pound force/pound mass.

The panel suspects that the limits are being approached in what can be accomplished with solid propellant chemistry given the restrictions of insensitive munitions, muzzle pressure, service life, overall weight and balance of the gun system, and so on. The panel is not ruling out evolutionary changes that may occur, but it does not see any major breakthrough other than what is discussed below in connection with the electrothermal-chemical (ETC) gun.

Liquid Propellants

Although the impetus values of liquid propellants (LPs) tend to be lower than those of solids, there have been compelling reasons for investigating them as replacements for solids. Some of these reasons were cost, logistic simplicity, safety, and the idea that tailoring the pressure wave as the propellant burned could make up for the lower impetus. Although the original bulk-loaded cartridge cases were unsuccessful because of erratic, poorly understood pressure fluctuations, the advent of the regenerative liquid propellant gun gave new hope to liquid propellant advocates. The idea behind this approach is rather ingenious. Propellant is injected into a chamber and as it burns, the increased pressure drives a piston backwards causing more liquid to be injected into the chamber. In principle one can dial a muzzle velocity, a very nice feature in any gun. In practice this has not been possible and the Army, which had the gun in development, opted for zones just as the solid-propellant gun uses. There are other problems with the gun. It is very difficult to seal a gun chamber operating at high pressures in the absence of a cartridge case or obturating pad. In the LP gun, this is complicated, since the seals move and sealing has to occur on two concentric diameters so that manufacturing tolerances work against a reliable seal. Liquid propellants burn stoichiometrically so that the exhaust products are highly corrosive. In the Army program, there have been some unexplained pressure fluctuations and blowups. Although the panel was not briefed on the current status of the Army program, LP guns do not appear to be a good investment for the Department of the Navy at this time.

Electric Guns

There are three types of electric guns, namely:

- The electrothermal-chemical gun,
- The electromagnetic (EM) rail gun, and
- The electromagnetic coil gun.

The ETC gun began as an electrothermal gun. The idea was to use material with a lower molecular weight than solids and dump enough electrical energy into it to create a plasma that then drove the projectile. Early attempts were made in small-caliber launchers using water or hydrogen peroxide. It soon became

apparent that enormous amounts of energy would be required for a gun of any size just to create the plasma. At this point, the emphasis shifted to using standard solid propellants or slurries with a plasma initiator and the result was the electrothermal-chemical gun. DARPA has been funding research in this area and has achieved considerable success in extracting more of the energy from a propellant than can be obtained with conventional primers. Thus ETC provides a means of going to higher loading ratios. Indeed, experimental results indicate that the Navy's 5-in./62 might achieve a muzzle energy of 25 megajoules versus 18 megajoules. The U.S. Navy is aware of this but has opted to go with the lower risk program outlined above.

Electromagnetic propulsion is a familiar concept. Perhaps the best known example is that of two fixed conductors in a magnetic field joined by a sliding wire contact. When a current is passed down the fixed wires and through the sliding contact, a Lorentz force is developed that accelerates the contact causing it to move down the wires. This is the simplest example of an EM launcher (EML).

The rail gun, whose simplest manifestation is described above, is best suited for low-mass, high-speed applications. It has had sporadic development effort over the last 45 or 50 years. At one time it was the hope of high-velocity investigators for launching aerodynamic models at very high velocities for high-mach-number, ballistic-range studies. However, it never lived up to its potential and never equaled the velocities that could be achieved with light gas guns. In more recent years, it has been considered for everything from fire support to close-in weapon defense with maximum velocities of the order of 8,000 to 10,000 fps. Although there are no theoretical stumbling blocks from the physics standpoint, there remain some challenging engineering problems. The present Army-funded program is aimed at developing a 90-mm antitank gun. This is scheduled to be tested within the next year. Nevertheless, at this time, the panel does not consider the rail gun as a viable option for the Navy.

The coil gun, a coaxial accelerator, is more complex than the simple example given earlier. It depends on magnet-to-magnet interactions and is best suited to high-mass, low-speed applications. Although the equivalent magnetic pressure that drives the projectile is lower than the thermodynamic pressure of conventional guns, the possibility of maintaining a constant force on the base of the projectile overcomes this deficiency and leads to a higher average pressure. At this time there are no significant showstoppers with the entire concept, but no one is funding its development. Earlier development was proof of principle and was confined to short-barrel (only a few magnetic coils), low-speed shots.

Besides developments in interior ballistics technology, there are exterior ballistics technologies that can be used to increase range. The most promising of these are RAPs and ScramShell. RAP rounds are projectiles that are launched from a gun and contain one or more additional rocket stages that are fired as the projectile travels to the target. Thus, the gun acts basically as the first stage of a

multistaged rocket system. The late Dr. G.V. Bull[9] had designs for RAP rounds to be launched from a 16-in. gun that achieved ranges of thousands of miles with payloads of several hundred pounds. ScramShell[10] is a projectile design, developed by Rockwell International, which consists of a supersonic ramjet. Rockwell has demonstrated the feasibility of this concept and has suggested several applications for this technology for both gun-launched projectiles and missiles. One of these is a conceptual design of the ERGM round fired from the 5-in./62 gun to a range of 100 nautical miles.

Summary

As far as guns are concerned, bigger is better and they scale quite nicely. Thus, if a 5-in./54 gun is scaled up to a 16-in. size, the result will be a gun very close to the Navy's 16-in./50 which could launch a 1-ton projectile to a range of 39 nautical miles (72.3 km). Any development work on the 5-in./62 can therefore be scaled up to a larger gun size, which will provide a commensurate increase in range and warhead lethality. The Center for Naval Analyses (CNA) conducted a Fire Support Cost and Operational Effectiveness Analysis (COEA)[11] that concluded that a mix of guns and missiles was the most cost-effective and that the most cost-effective gun was a 155 mm. An attractive option for an arsenal ship would be to mount a pair of 155-mm guns in one cell of the vertical launcher. These guns would have muzzle energies of 27.5 megajoules (200-lb [91-kg] projectile at 2,550 fps [777 m/s]) and would load automatically. Such a system could fire at a rate of 5 to 10 rounds per minute per gun. It would leverage off of the developments in the present 5-in. program and could eventually use ScramShell propulsion.

Based on anticipated improvements in GPS (e.g., WAGE 1 and WAGE 2) and anticipated future developments of inertial measurement units, delivery location accuracies relative to aim points of 1- to 3-m CEP should be achievable. The target location error (TLE) of fixed targets should be known with equal accuracy. The TLE of relocatable tactical targets may be anywhere from 1 to 50 meters depending on the sensor used to locate the target. Targets located by ground observers using laser range finders will probably have TLEs in the range of 1 to 10 meters. Those located by remote sensors will be greater.

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[9]Bull, G.V., and C.H. Murphy. 1988. *Paris Kanonen—The Paris Guns (Wilhelmgeschutze) and Project HARP*, Verlag E.S. Mittler and Sohn GmbH, Herford und Bonn.

[10]Rockwell International. 1996. "Air-Breathing Powered ScramShell Supports Naval Surface Warfare," briefing to the panel at the Center for Naval Analyses, Alexandria, Va., April.

[11]Sullivan, Robert E., J.M. Stanford-Nance, B.G. Pifer, L.J. Kusk, J.D. Love, J.M. Dowd, and V.C. Dawson. 1994. *Naval Surface Fire Support Cost and Operational Effectiveness Analysis, Final Report,* CNA-RAS 210, Center for Naval Analyses, Alexandria, Va.

The panel's analysis shows that even with GPS/INS accuracies as high as 10 meters and submunition warheads like SADARM and DPICM, the TLEs need to be about 50 meters in order to avoid a 20 percent increase in the number of rounds of any given warhead size to kill the target. The analysis was based on warhead weights of 40, 70, and 125 lb, i.e., typical gun warhead weights. The panel does not believe that the results will change when larger warheads, such as are possible with missiles, are used. Thus, there is always a need to improve targeting accuracy regardless of the weapon system employed.

Based on its examination of current or projected technology the panel came to the following conclusions:

- ETC can provide a 25 percent or greater improvement in the range of naval guns such as the advanced 5-in./62 that is being developed.
- Rocket-assisted projectiles offer the potential for large increases in range.
- Except for harassment-type fires, guided projectiles are absolutely essential with any gun system. Given the logistics burden imposed by harassment fires, tactics that exploit PGMs to minimize the need for harassment should be developed.
- The liquid-propellant gun, rail gun, and coil gun are not recommended for Navy development, but any Army programs should be followed with interest. The panel does not believe that all of the capability that can be realized with solids has been achieved.
- With regard to the various concepts for electromagnetic guns, the panel believes that even if they perform as hoped, they will be overtaken in time by more advanced concepts for solid-propulsion or low-cost missiles.
- For VLS-type ships, the Department of the Navy should consider vertical mounted guns of 155-mm diameter that automatically load and fire guided RAP rounds. Two such guns could be mounted in a single cell.
- The most serious problem facing the naval forces in fire support is not the type of launcher to use but how to locate and localize relocatable targets within the required accuracies. This is the area that needs emphasis.
- Naval fire support should consist of a mix of gun-fired projectiles and missiles, with the balance shifting progressively toward missiles. The Navy Department should concentrate on reducing the cost of these items.
- The panel believes that the gun system that will evolve for the naval forces of the next century will consist of a pair of 155-mm guns with a muzzle energy of 30- to 35-megajoules firing ERGM (ScramShell) projectiles weighing over 200 pounds. These guns will be mounted vertically in one cell of a VLS, will load automatically, and will fire at a rate of 5 to 10 rounds per minute. The gun propellants will be primarily solids with ETC ignition. A variety of warheads will be available, including HE, DPICM, SADARM, and BAT. All of the projectiles will have a terminal seeker and/or GPS/INS guidance except those devoted to area fire.

SURFACE-TO-SURFACE AND AIR-TO-SURFACE WEAPONS SUMMARY

Based on its review of current and evolving technology, the panel believes that over the next 25 to 35 years there is a good likelihood of realization of the following:

- An improved C^4I/reconnaissance, surveillance, and target acquisition (RSTA) system that will allow the safe and effective use of surface-to-surface and air-to-surface weapons for
  - —Strikes against fixed and stationary targets,
  - —Strikes against many classes of moving targets,
  - —Support of engaged troops ashore;
- Precision-guidance and weapon-sensor systems that will allow weapon delivery to within 1 to 3 meters of the aim point;
- Families of relatively low-cost modular-design precision missiles with interchangeable second-stage weapons (separate boosters for air or sea launch);
- Tailored warheads for
  - —Soft area targets,
  - —Structural targets (buildings, bridge abutments, and tunnels),
  - —Targets with unique signatures (tanks, trucks, artillery, and EM radiators);
- Weapon sensors and two-way data links that allow aim point adjustments and preimpact weapon report back for BDA; and
- Gun-launched projectiles with ranges of about 60 nautical miles (110 km).

If these weapon concepts are realized, there will be profound impacts on the effectiveness and timeliness of response of naval forces. Within the limits of individual weapon point designs, air- and surface-delivered weapons will become mission interchangeable. Air-to-surface delivery of weapons will tend to be reserved for situations such as the following:

- The pilot's capabilities for visual observation of the target and final judgment are required.
- A weapon must loiter close to the probable emergence point of an extremely ephemeral target (e.g., pop-up artillery or Scuds).
- Targets are beyond the 600-km treaty range limit for ship-launched ballistic missiles.

The panel believes that, whether weapons are ship- or air-launched, the long-term trend will be toward the use of long-standoff weapons. As a general matter, the launch platform will derive its knowledge of target location and type from remote sensors (including forward observers) and from data generated by a C^4I/RSTA system that allows a battle manager (whether afloat or ashore) to use his or her weapon resources as effectively as possible. As the attributes of air-to-

surface and surface-to-surface weapons converge, their costs should converge as the only differences will be in first-stage propulsion. Choices of air or surface delivery will be determined by operational considerations such as range to target, response time for weapon delivery, and ability to abort weapon delivery if a human observer determines that an attack on a target is inappropriate.

The panel believes that weapon systems with the foregoing capabilities are certainly achievable within the next 25 to 35 years. The achievement of the capabilities discussed herein will require a continuing investment in the following areas listed in rank order of priority:

- Sensors,
- C^4I/RSTA,
- Weapon guidance and control,
- Tailored warheads and submunitions,
- Design of families of modular missiles that can be air- or ship-launched, and
- Propulsion and explosive energetics.

4

Air-to-Air Weapons

BACKGROUND

Assumptions

The future air-to-air environment will be significantly different from the current environment in many respects. Although the direction in which technology is developing is reasonably clear, there are many uncertainties to consider. The panel concluded that certain assumptions needed to be made to address these uncertainties.

Air superiority will continue to be the sine qua non of large-scale military operations, and the Navy will seek air-space dominance in its areas of operation. The principal vehicle to attain that dominance will continue to be manned aircraft, which will serve the dual role of strike and air superiority as part of the broader power-projection mission. Although the panel believes that there will be a shift in emphasis to surface-launched strikes against ground targets using precision-guided rockets, the need for multirole aircraft for a variety of missions will not disappear. The air-superiority mission alone dictates an air-based capability. The best investment is a balanced air superiority and strike system with other ancillary capabilities. Although unmanned or uninhabited fighter aircraft are technologically possible, the perceived need for positive on-board control of a platform carrying highly destructive materials and capable of destroying multiple aircraft or ground targets in a few seconds will be a dominant consideration well into the future. This assumption affects platform weapon tradeoffs as the limitations of the human body will continue to restrict aircraft performance. The trend

toward automation will certainly continue, and it is likely that unmanned fighter-type aircraft will be developed and tested within the horizon of this study. Whether, and in what time frame, technology will prove adequate to permit the pilot effectively to fly and fight an aircraft from a remote location at the end of a data-and-command link is a matter of speculation. Here, the panel assumes the continued presence of a pilot in the cockpit; this assumption affects platform tradeoffs, which are thereby constrained by the limitations and support requirements of the human body.

Future opponents are unlikely to match the United States in terms of aircraft quality. An advanced technology fighter development program with a price tag the equivalent of $20 billion is beyond the reach of any other current power and would require the emergence of a peer competitor and a decade of development. The panel does believe that future opponents will acquire aircraft approximately one generation behind U.S. designs and will selectively design competitive capability in ancillary areas such as air-to-air missiles and countermeasures.

An important assumption is that the current move toward integration of sensors with cooperative engagement capability (CEC) levels of performance will continue and be extended to all tactical platforms. This development fundamentally changes the nature of the air-to-air arena by enabling off-board contributions across all air-to-air functions from detection through engagement. The Navy will continue to lead the evolution toward air operations characterized by much more highly integrated capabilities.

Major Issues and Drivers

In assessing the alternatives to future air-to-air weapons, the panel recognized four factors that will fundamentally affect future air-to-air operations: (1) operational contexts, (2) threat capabilities, (3) nonweapon U.S. air-to-air developments, and (4) technological opportunity. A discussion of each of these subjects follows.

Operational Contexts

The panel does not anticipate that the current spectrum of naval air operations will fundamentally change. The drivers in the operational context include the required degree of combat ID (rules of engagement) and the relative numerical advantage or disadvantage enjoyed by naval fighters. The panel envisioned three general classes of engagement context.

The first of these is the type of operation sometimes called operations other than war (OOTW). This includes no-fly-zone enforcement, patrolling in support of peacekeeping, and operations prior to hostilities in the vicinity of a potential adversary. These operations are characterized by very tight rules of engagement and correct combat ID is a paramount consideration. Although beyond-visual-

range (BVR) identification is possible, the degree of confidence desired to prevent engagement of a friend or neutral or even unjustified engagement of an adversary is quite high. As a result, short-range encounters (often for visual identification) will occur, resulting in short-range engagements. In such circumstances, a local numerical advantage is unlikely although parity or something close to it will probably be the norm.

The second class of operational contexts, initial hostilities, is the most dangerous to naval aircraft. In a typical situation in this category, hostilities may just have commenced and the adversary may possess a local numerical advantage. Rules of engagement will be relatively loose as a result, and engagements at various ranges (short, medium, and long) can be expected. Full off-board support for combat ID may not be present, and there is a high premium on attacking and defending key assets.

The final operational category is characterized by a more stable situation in which the United States has built up forces to the extent that a numerical advantage has been achieved; there is significant off-fighter support for surveillance, electronic warfare, and other functions; and the rules of engagement are fairly tight. In this case, long- and medium-range engagements should dominate as situational awareness can be very high, neutrals should not be encountered, and visual identification should not be a requirement. Ideally this could apply to the previous situation as well, but the panel was not ready to assume this would occur.

The panel concluded from the considerations above that a mix of weapons capabilities (short, medium, and long range) would continue to be required. If highly reliable BVR identification can be developed, however, the significance of short-range air-to-air weapon capability would be significantly reduced.

Threat Capabilities

Although the United States has made a substantial investment in stealth aircraft, our adversaries do not appear to have followed suit. The panel believes that a limited degree of stealth can be expected on threat aircraft, primarily from the frontal aspect. It is unlikely that a competitor will develop designs like the F-117 or B-2 or even F-22 and JSF, which are highly stealth-oriented. The technological lead possessed by the United States and the investment required are prohibitive. Some stealth technologies, on the other hand, such as radar-absorbing material and basic shaping, are fairly well understood and widely available. As a result, a modest degree of stealth in threat aircraft can be anticipated. A much greater degree of stealth can be anticipated for cruise missile and UAV threats where the size, function, and geometry of the vehicle are much more amenable to stealth design or retrofit. Assuming detection and identification can still be accomplished to the same level against these threats, then weapon seekers and fuses must be designed to respond as well. This requires enhanced power

aperture performance and the use of alternative portions of the electromagnetic spectrum (MMW and IR) to avoid regions in which LO technologies are most effective.

In the short-range engagement zone, the United States is currently at a disadvantage. The aging AIM-9 inventory lags behind systems such as the AA-11 and Python-IV, which are characterized by high off-boresight seekers, agile airframes, advanced imaging IR sensors, and countermeasure capability. The true fire-and-forget nature of short-range systems makes this engagement area highly lethal to all combatants. In many scenarios two adversaries successfully launch resulting in mutual destruction. The U.S. Navy should either seek a decisive advantage in this region or find a way to dominate at longer ranges, obviating the need for close-in engagements. As discussed earlier, combat ID capabilities and required operational contexts make the latter option problematic in some scenarios.

Threat capabilities are also improving in the medium and long engagement-range categories. The U.S. AMRAAM was the first quasi-fire-and-forget, medium-range weapon (AMRAAM requires midcourse updates until the seeker acquires the target). However, this technology will proliferate and we can expect long-range surface-to-air or air-launched RF-guided missiles to threaten our assets, particularly high-value assets like E-2, JSTARS, airborne warning and control system (AWACS), and so on. In addition, the United States can expect antiradiation homing threats and reasonably sophisticated electronic and IR countermeasures and counter-countermeasures.

One area in which we can expect other threats to be competitive, but generally lag behind the United States in level of capability, is in countermeasures to our weapons. RF and IR jamming, towed decoys, and other countermeasures will evolve to respond to emerging weapons capabilities. In this area the possibility of technological surprise is reasonably high and should be a major concern.

Nonweapon U.S. Air-to-air-related Developments

General

Weapons design cannot be conducted in isolation. Although this has always been true, the degree to which nonweapon development affects design is expected to increase. In general, combat capabilities are evolving toward more integrated and complex systems of systems. This is certainly true in air-to-air combat. As a result, weapons/aircraft trades are taking on new dimensions and complexity.

The most significant development now emerging is the proliferation of CEC technology. The most significant impact of this development is the added opportunity for long-range engagements. Current weapons are highly reliant on onboard sensors to detect, track, and hand over targets to weapon sensors. The size and hence aperture limitations on highly maneuverable fighters designed for dog-

fighting agility limits the range of on-board fire-control sensors. Off-board sensors, possibly multistatic, which are closer to the target and/or located on larger platforms will permit long-range engagements. Synergistically, as long-range engagements are enabled the need for short-range air-to-air capability (and consequently for highly agile fighters) diminishes.

The extensive investment in stealth technology by the United States dictates that air-to-air weapons be stealth compatible. This requirement can be met through internal carriage, which raises the premium for reduced-size weapons and/or for design of the weapon and platform as an integral LO package (before and after weapon launch).

A benefit of networked tracking systems is that more assets, including surface assets, can be employed in defense against coordinated aircraft and/or missile attacks, particularly attacks on the high-value assets mentioned earlier. This concept, which argues for both long-range air-to air (AA) and surface-to-air (SA) weapons, is discussed in the surface AAW section also.

Combat ID remains problematic in many scenarios. The panel envisions that the United States will continue to invest in both cooperative and noncooperative techniques. Enhanced situational awareness, achieved through integrating all available sensor data, may provide the best way to address this issue. Surveillance systems that can track threat aircraft from origin would essentially resolve this issue if the networking to interconnect such sensors could be relied upon. The panel has concluded that the Navy and the United States are progressing toward that goal and should achieve it in the study time frame. This implies that long-range engagements can be enabled in all but the most restrictive of scenarios.

Another related development that could have an impact on the U.S. ability to rely on longer-range weapons is the advent of stealth UAVs that will be forward deployed on surveillance assets to enable early engagement of ground or airborne targets. A study conducted recently by the Air Force has endorsed this concept.

The following section discusses the highly important subject of preserving future networked capabilities in the face of LO threats. A conceptual approach to resolving this issue is suggested.

Technology to Improve Detection of Low-observable Targets and Achieve Reliable Target Identification at Long Ranges

The current concept of operations (CONOPS) for air-to-air combat is that an airborne early warning (AEW) aircraft such as the Air Force's AWACS or the Navy's E-2C using high-performance radars will detect hostile aircraft at long distances and alert fighter aircraft to their location. When a fighter aircraft acquires the target with its own on-board sensors and can establish the target's identity well enough to satisfy the local ROE, it is then able to release a weapon.

In the past when detection ranges were not degraded by LO, air-to-air engagement ranges were generally driven by the range at which identification could be

established. Identification was established by some combination of electronic challenge (IFF), the detection of radiation (ELINT or ESM), the detection of a characteristic modulation of the returned pulse, or the construction of tracks that indicated a hostile trajectory. As the radar cross section (RCS) of hostile aircraft is reduced, both the detection range and the ranges at which identification can be achieved will be reduced and the probability of short-range encounters will be increased.

The operational advantage provided by an ability to detect and identify hostile aircraft well beyond weapon engagement range is obvious. Both the Air Force and the Navy have, have had, and will probably continue to have vigorous programs to upgrade the performance of the radars in the AWACS and the E-2C. The results achieved to date are impressive, and if current programmatic goals are achieved, future performance of these crucial radars will be enhanced significantly. Unfortunately, the projected improvements in the performances of AEW radars do not in themselves guarantee the necessary range detection margin against LO aircraft needed to assure the reliable use of medium- and long-range air-to-air weapons.

Designers of LO aircraft and cruise missiles are also attempting to further reduce the signatures of aircraft to negate any improvements that may reasonably be projected for future AEW radars. Based on information available to it, the panel has no reason to believe that the designers of AEW radars will ever achieve a robust advantage against LO missile targets and, as a consequence, has concluded that an alternate approach to the primary dependence on monostatic AEW radars must and will be used in the future.

Low RCSs on aircraft or missiles are generally achieved by some combination of shaping of the aircraft's surfaces together with the use of radar-absorbent materials (RAMs) as surface coatings.[1] The applications of these technologies tend to reduce the nose-on back-scatter and thus degrade the performance of a monostatic radar. The applications of these primitive stealth techniques have limitations in the sense that they generally do not produce all-aspect stealth at all possible radar frequencies. Although the aircraft's nose-on RCS may be reduced significantly, there will be other directions where strong signals (glints) occur. Depending on the geometry of the situation, a properly oriented monostatic radar may have little difficulty detecting LO aircraft and missiles that employ first-generation stealth technology. Such situations occur when the radar views the target from other than a nose-on direction. Indeed the Navy's remarkably successful CEC is based on this principle. In the CEC system multiple monostatic radars (each viewing the target from a different bearing angle) are linked together into a network that allows the data from all radars to be jointly processed. The probability of detection and track formation is thus greatly improved.

The panel is convinced that the ultimate answer to the problem of long-range detection of LO aircraft does not reside solely in the achievement of performance

[1]Ufimtsev, Pyotr Y. 1996. "Comments on Diffraction Principles and Limitations of RCS Reduction Techniques," *Proceedings of the IEEE,* 84(12):1830-1850, December 12.

improvements in AEW radars. Such improvements are necessary and should continue to be pursued as high-priority programs. What appears to be necessary is the extension of CEC to support air-to-air combat.

The panel believes that the potential of a CEC system designed to support air-to-air combat is at least as great as the potential of a CEC system designed to support surface-ship defense. In the airborne case, the sensor network could be expanded to include all IR (and, if available in the future, active laser) detections in addition to the detections of all available airborne and ground-based monostatic radars.

Ultimately, the power of an airborne CEC would be further enhanced by the addition of a multistatic radar capability in addition to monostatic capabilities. Conventional radar textbooks[2] generally point out that the ratio of the forward-scatter energy to the back-scatter energy, $4\pi\ (A/\lambda)^2$, is related to the projected area of the target. Depending on the area involved and the wavelength of the radar being used, forward scatter may be many orders of magnitude greater than the back-scatter RCS. Contemporary techniques to achieve low observability do not affect this ratio.

Unfortunately it is difficult to use a forward-scatter signal because the signal has zero Doppler shift and any receiver in a position to detect a forward-scatter signal would be overwhelmed by the direct path signal from the transmitter. The only hope for the successful design of a bistatic or multistatic signal is for the receiver to be positioned at some angle other than 180 degrees. The well-known Babinet's principle tells us that off the forward-scatter direction, the forward-scatter ratio given above varies in a $\sin(X)/X$ pattern where X is a function of bearing angle, wavelength, and target dimensions. Thus, as the receiver moves away from a forward-scatter geometry, the Doppler shift of the scattered signal increases from zero, thus improving detectability. This is offset to some degree by the fact that the signal amplitude decreases according to Babinet's principle. In effect, if the complexities of implementation of multistatic radars can be resolved, first-generation stealth technology could be nullified.

Thus, the implementation of a networked system of sensors that include improved AEW and combat aircraft radars, IR detectors, laser radars, and multistatic radars could provide a detailed picture of the aerial battle space at increasingly longer ranges even for LO targets. Information from the network of sensors can be provided to the cockpit of modern fighter aircraft where it can be combined with the aircraft's own sensor picture for the identification and targeting of enemy aircraft at very long ranges and with a high degree of accuracy.

Particular challenges for these netted detection and identification systems are the proliferation of both Russian and Western aircraft on the world market. Noncooperative target-recognition techniques, often based on engine or sensor characteristics, will have to be refined and expanded to allow friends to be distinguished from foes accurately.

[2]Skolnick, Merril I. (ed.). 1970. *Radar Handbook,* Chapter 36-6, McGraw-Hill, New York.

The panel believes that evolving technology will allow the resolution of all of the challenges discussed above and that future network sensor systems will be able to negate the impact of current stealth designs. Under such circumstances, hostile aircraft should be detected and reliably identified at ranges that will permit a primary dependence on medium- and long-range air-to-air missiles.

Technological Opportunity

The panel reviewed the ongoing air-to-air weapon-related technology developments. Most technologies associated with air-to-air missile designs are progressing in an evolutionary manner with no real evidence of a likely breakthrough. Nonmissile concepts are receiving relatively little attention. One area of interest is solid-state lasers, which in combination with an all-aspect missile approach warning and tracking system offer interesting possibilities for active defense in a short-range lethal engagement of the attacking missile. A brief discussion of the relevant missile and nonmissile technologies follows.

Missile Guidance and Control

The fundamental guidance schemes (command, semiactive, and active) have evolved toward greater on-board capability. Continuous improvements in autopilot performance and response times have been made. For controls, reduced weight and increased control authority through thrust-vectored control characterize emerging missile systems. Reaction controls will be developed in the study time frame to reduce miss distance and respond to target maneuver. Hit-to-kill is a possibility for air-to-air engagements; however, for the foreseeable future, warheads that require proximity fuzing will be required. Missiles will have an increasing advantage over manned aircraft in the study time frame eclipsing any increases in aircraft maneuverability.

Propellants

Current propellant research is focused on marginal improvements in specific impulse (tens of percent of current levels). Traditional chemical propellants are approaching the apparent limits of technology. Novel schemes such as hybrid propellants and progressive propellants can substantially improve average velocity and range, however. Inasmuch as shipboard safety will remain a paramount concern for naval applications, these technologies will be developed for land-based applications first. Since the panel believes that longer-range engagements should be emphasized for the future, we support continued research in this area.

If successful, ongoing research involving new classes of metastable materials offers the potential for the achievement of enhanced energy release from explosives and propellants. The research is based on the concept that metastable molecular and

atomic states might be created that would contain more bound energy per unit mass than can be released by chemical reactions. If such states could be shown to have long-term stability and could be triggered at will to decay to ground states, then more energy could be recovered than is now recovered from existing explosives and propellants. The panel recognizes that research in this area is in its infancy, and at this time there is little if any reason to expect practical applications to arise from this effort within the next 35 years. Explosives and propellants combine metastable molecules that yield energy when detonated or combusted to a set of stable chemical products. A potential breakthrough in energetic materials may be derived from concepts that significantly enhance this difference between the original metastable state and the stable products essentially by creating molecules with far greater initial metastability. One of these concepts is in an extended solid in which the chemical bonding is transformed to significantly greater numbers of energetic bonds as opposed to a few internal energetic bonds and weak bonding between molecules. An example of this is the conversion of diatomic nitrogen to a polymeric form of nitrogen. Hence the term extended solid. An early proof of principle exists in solid polymeric carbon monoxide, which has been synthesized. Carbon monoxide is isoelectronic with nitrogen.

The panel recognizes that these concepts and the attendant research are in their infancy and must be considered as high-risk ventures. However, the potential for a breakthrough merits a sustained program in this area.

Warheads and Fuses

Similarly to propellants, warhead technology can be expected to evolve incrementally. Safety remains a paramount concern. In the study time frame, selectively aimable warheads and warheads containing reactive material are viable options that should be pursued (as discussed above, metastable materials offer a potential, albeit highly speculative breakthrough in this area).

Fuzing technology must evolve to enable future missile design capability against stealth targets, particularly against cruise missiles. As seekers evolve toward advanced imaging systems and as off-boresight capability increases, resolution increases, and endgame response improves, it will be possible to integrate the fuse function within the seeker function. This will save weight and improve performance. Future fuses will consist of four elements: (1) target identification, (2) initiation train, (3) safe-arm device, and (4) power source. Technological developments in each component area are proceeding.

Seekers

Seeker designs will be driven by the appetite for increased acquisition range enabling greater fire-and-forget engagement capability. The presence of even modest stealth forces innovative approaches involving multimode seekers. The

countermeasures and counter-countermeasures game will continue and increase the appetite for high-resolution imaging or quasi-imaging capability. Commercial processing should support the data-processing requirement of seekers; however, signal processing and algorithm development must continue to keep pace with ever-improving countermeasures. These requirements are uniquely military. The next phase in this development will be electronically scanned arrays followed by conformal arrays and multimode conformal arrays.

Nonmissile Technologies

The panel did not see a future for gun systems as an air-to-air weapon of choice. Directed-energy weapons, however, do offer some promise in the study time frame. Solid-state lasers, in particular, are developing at a pace that should enable their application in active self-defense suites in the near future. The initial application would be to counter IR-guided missiles employed with an all-aspect missile-approach warning system, probably also working in the IR band. If weight and power/efficiency parameters for these lasers continue to improve, an expanded role is possible, including defense against radar-guided missiles, cruise-missile engagement, and close-in aircraft engagement.

ALTERNATIVES

The panel considered a range of weapon alternatives for the future. The panel focused on missile options because it believes that these will continue to be the weapons of choice. Table 4.1 provides the options considered in the short-, medium-, and long-range categories. These options are characterized more by the approach taken than by specific design or technology. In all categories, a status quo or minimal program is hypothesized followed by more aggressive options. These are discussed in the following paragraphs.

Short Range

The panel concluded that the status quo of maintaining AIM-9M with limited preplanned product improvements (P^3Is) such as the one currently under way is inadequate. Potential threat systems, including AA-11 and export versions of other systems, have surpassed the AIM-9M and minor P^3Is will not restore parity. AIM-9X incorporates a philosophy of design oriented on processing improvements, CCM algorithm development and kinematic growth. For the near future (initial operating capability [IOC] to 15 years) this approach should be adequate. Other P^3Is (warhead and fuse, more capable IR detector, and so on) may be attractive options at a later date. The concept of a highly agile, hypervelocity, kinetic-energy, close-in all-aspect defense weapon has some attractive features. However, the technological challenges are formidable, and a DEW approach using solid-state lasers as described earlier seems more attractive to the panel.

TABLE 4.1 Missile Weapon Alternatives

Short Range	Medium Range	Long Range
Status quo with P^3Is	Status quo with P^3Is	No capability
AIM-9X and P^3Is	Multimode AMRAAM replacement	Extended-range semiautonomous missiles
Hypervelocity agile missile		
DEW		

Medium Range

The AMRAAM system is currently the leading medium-range air-to-air weapon system in the world. Currently planned P^3Is will enhance its capability in selected areas such as warhead performance and counter-countermeasure capabilities. Longer-term P^3Is could include advanced seeker designs using electronically scanned arrays, possibly conformal arrays, and multimode seekers. A range-extension program with reduced drag and a boost/sustainer configuration would be attractive. The alternative to further product improvements is a new medium-range system that incorporates similar advanced technologies in a bottom-up design. As technologies mature, this option can remain available until cost-effectiveness arguments justify a new development program. At present, continuing to improve AMRAAM appears to the panel to be the best strategy. By the end of another decade, however, technology should have developed to the point where an AMRAAM P^3I would have little resemblance to the original AMRAAM.

Long Range

The aging Phoenix system is the only long-range asset in the U.S. inventory. Designed to counter Soviet cruise-missile-carrying bombers, it is not a system responsive to today's or tomorrow's needs. There are technology programs in place to develop suitable capabilities for a future long-range air-to-air missile, but their near-term focus is on short- and medium-range all-aspect engagements. The panel believes that a CEC-like air-to-air environment dictates a need for a long-range capability. One route to this capability is an AMRAAM P^3I. Another is a new advanced-technology long-range interceptor.

Tradeoff studies between these options should be carried out. In this context, full consideration should be given to available air-to-air system-of-systems tradeoffs. Even with advanced-technology multimode seekers, a long-range interceptor will require midcourse updates prior to target acquisition by the seeker. To the extent possible, a semiautonomous fire-and-forget capability should be provided. Commonality between an upgraded medium-

range capability (AMRAAM P^3I) and a new missile satisfying both medium- and long-range requirements should be considered.

FINDINGS

General findings are as follows:

- For the foreseeable future, missiles will be the weapon of choice for air-to-air engagements.
- The U.S. advantage of superior pilot training and performance will diminish as fire-and-forget missiles increasingly dominate air combat.
- Various operational contexts will require a mix of short-, medium-, and long-range air-to-air capabilities, but the emphasis will shift to long-range engagements.
- Aggressive developments in countermeasures and counter-countermeasures should continue but will always have some degree of fragility against uncertain threat responses.

Specific findings for short range are as follows:

- Weapon time of flight will continue to dominate short-range engagements, often resulting in mutual destruction.
- Current U.S. capabilities are behind the threat. AIM-9X will regain parity and some advantage over threat missiles.
- Enhanced countermeasures are necessary to prevent mutual-destruction engagements.
- Hard-kill countermeasures (active self-protection) will be necessary to counter close-in aircraft and air-to-air missiles. Solid-state lasers offer the potential to perform this function.

Specific findings for medium range are as follows:

- AMRAAM and AMRAAM P^3I will provide an advantage for the next decade.
- Beyond that point, a multimode replacement with an electronically scanned dual-mode active array and advanced propulsion will be attractive.

Specific findings for long range are as follows:

- Networked capabilities can only be fully exploited if a long-range (> 100 nautical miles) air-to-air missile is developed and fielded.
- Weapon/platform tradeoffs will need to be considered carefully as part of the concept definitions of this missile.
- Development of this system should begin in the near future to synchronize its fielding with a full airborne CEC capability.

RECOMMENDATIONS

The panel submits the following recommendations in order of priority:

- Initiate a concept definition for a long-range interceptor (> 100 nautical miles) to include weapon/platform tradeoffs as part of a broader air-combat system study.
- Replace AIM-9M as planned.
- Aggressively continue the current evolutionary program of countermeasure and counter-countermeasure development.
- Conduct a technology program to develop key technologies for a laser, active self-protection system.
- Pursue a multimode upgrade or replacement for AMRAAM.

5

Defensive Systems

BALLISTIC MISSILE DEFENSE

It is the view of the Panel on Weapons that the role of the naval forces in ballistic missile defense (BMD) and the potential technical, operational, and cost implications over the next 25 to 35 years will be the following:

- Theater ballistic missiles will proliferate
  —as an important delivery system for weapons of mass destruction (WMD), and
  —as a means of accurate conventional attack on fixed targets and surface ships.
- Without competent theater ballistic missile defense (TBMD)
  —amphibious operations and land attack will be difficult and risky,
  —the standoff range of surface forces will have to increase, and
  —strike and shore bombardment from submarines and long-range aircraft will dominate.
- The naval forces have a key role in TBMD, including
  —initial emphasis on short-range terminal defense,
  —later evolution to long-range pre-apogee intercept, and
  —attention to current gap in sea-based boost-phase intercept despite need/opportunity.
- Navy TBMD has multimission potential, including
  —antiair,
  —limited defense of U.S. homeland, and
  —space control.
- Threat evolution requires a strong technology program—key is a joint effort with the Ballistic Missile Defense Organization (BMDO) and the other Services.

Navy Theater Missile Defense

Background

The Threat

Today nearly 40 countries possess theater ballistic missiles (TBMs), and all indications are that proliferation of the missiles will continue unabated. At the same time widespread proliferation of so-called WMD—chemical and biological agents and nuclear devices—is occurring, and ballistic missiles will likely be their principal delivery system. In recognition of the seriousness of these two trends, the White House recently declared (Executive Order 12938) "a national emergency to deal with WMD proliferation and the means of delivering such weapons."

Figure 5.1 depicts the magnitude of the TBM threat today. For many years the primary threat will be short-range TBMs with ranges of 300 to 900 km, such as the low-accuracy Scud and its slightly longer-range variations (Al Abbas and Al Hussein) used by Iraq in the 1991 Desert Storm conflict. Many mideastern countries and North Korea now possess these types of missiles. The short-range TBMs will become increasingly more accurate and will likely employ maneuvering and stealth reentry vehicles and penaids. In addition, they will be armed with submunitions (inert projectiles or filled with chemical and biological agents or high explosives) that today are normally dispensed after the TBM reaches its apogee, but could be deployed before apogee and even shortly after booster burnout. The primary targets of the short-range missiles will be debarkation ports, airfields, staging areas, amphibious objective areas, and concentrations of land-attack forces. The panel is concerned that the TBMs will be a powerful deterrent to future power-projection operations by the naval forces, especially when there is a strong possibility the missiles are armed with WMDs. In the early part of the 21st century, TBMs with terminal homing will make an appearance which, when combined with even rudimentary ship targeting, could present a serious threat to Navy ships in a littoral area.

TBMs with longer range (1,000 to 3,500 km), such as the North Korean No Dong 1 and 2 now under development and the Chinese CSS-2 and CSS-5, will become more plentiful in Third-World nations in the first decade of the next century. Over time, improvements will take place in missile accuracy and defense-penetration ability (maneuvering reentry vehicles, stealth, penaids, saturation via multiple-missile launch coordination, guided submunitions, and so on). The targets for these missiles will be the same as for the shorter-range TBMs; but the longer ranges will allow launch from safer standoff distances, and the higher velocities, maneuverability, and penaids will be able to penetrate first-generation short-range terminal defenses. It is expected that long-range TBMs armed with WMD will be used as the primary weapon for theater strategic deterrence, such as holding allied and coalition population centers hostage to dissuade U.S. interference in a crisis.

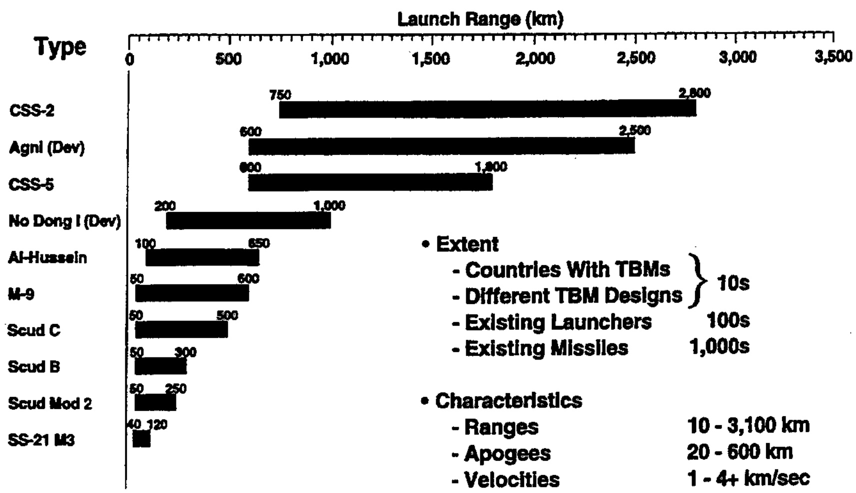

FIGURE 5.1 The real and growing TBM threat. SOURCE: Carlson, James D. 1996. "TBM Threat—Real and Growing," Ballistic Missile Defense Program Overview briefing for the Naval Studies Board, Ballistic Missile Defense Organization, Washington, D.C., presentation to the Panel on Weapons, August 5.

The bottom line is that without competent TMD, large-scale landings of surface forces will be unlikely and naval surface forces will need to stand off at safe ranges (avoidance) to reduce their vulnerability to the TBMs. Recently, for example, the Marine Corps has concluded from its analysis and war games that amphibious operations and land attacks in general would probably involve prohibitive losses unless a satisfactory solution is found to the TBM threat. This concern is not entirely novel. After World War II, General Eisenhower revealed that if Germany had deployed its V-2 ballistic missiles even 6 months sooner and had targeted English embarkation ports and facilities, the invasion of Europe could probably not have taken place. Ironically, even though the Scud missile used in the Persian Gulf War is nothing more than an upgrade of the V-2, the United States and our allies still do not have an effective defense against it. Advances in technology that would make possible an effective defense have yet to be successfully demonstrated.

Another consequence of the TBM threat to surface forces is that the Navy would have to become dependent on nuclear-powered guided-missile submarines (SSGNs) and long-range aircraft for strike and shore bombardment. Submarines have the advantage of being untargetable by TBMs, but unless Trident-size boats were employed, there would be a substantial reduction of firepower versus the use of large surface ships now planned as missile-launch platforms.

Why Sea-based TMD?

Since the Navy is usually the first on the scene in a regional crisis, sea-based TMD would be invaluable for holding the fort until ground-based or air-based defenses arrived and for enabling the early forcible entry by U.S. and allied/ coalition expeditionary forces. After the conflict's initial phase, the sea-based TMD could then be used to help protect the expeditionary forces as they advance inland, to defend ports supporting the expeditionary forces, and to defend newly established inland airfields. In addition, since Navy ships will normally be deployed at or near most future crisis areas, the theaterwide coverage of a long-range TMD system would provide a timely and cost-effective counter to any rogue nation's attempt to deter U.S. intervention by threatening allied and coalition population centers with their TBMs.

Sea-based TMD would have other attractive attributes, such as the following:

- It is rapidly deployable and sustainable without the air/sealift required for ground-based TMD. Sealift in many scenarios would just take too long. Even with modern aircraft involved, it would still take 1 to 3 weeks to organize and deliver one TMD battalion to the Middle East. And of course, this assumes that there is a willing host nation with at least a rudimentary airfield to accommodate large cargo aircraft such as C-5s and C-17s. Further, the airlift required to deploy land-based TMD batteries with their separate air defenses (Navy ships come with built-in air defense) would put a severe strain on the airlift capacity at the same time it is needed to deliver other vital military equipment into the conflict arena.
- It can provide theaterwide ballistic (and potentially aircraft) defense over the sea and littoral land area by virtue of having both short-range and long-range TMD systems on board the ships. The defense-in-depth pays off in a significant reduction in the number of TBM leakers.
- It can provide broad defensive coverage, since the ships' mobility allows them to be positioned closer to the TBM launch sites. And the enormous engagement footprints possible with long-range interceptors can make TBM defense more affordable.
- It can leverage the over $50 billion investment in the Aegis fleet (consisting of approximately 40 modern destroyers and cruisers with advanced SPY surveillance/fire-control radars, the Mark 41 vertical launch system [VLS], state-of-the-art satellite communications equipment, large-screen displays, and so on) and an extensive in-place and operating support infrastructure. As a result, the acquisition cost can be considerably less than for a land-based TMD system starting from scratch. In addition, the TMD Aegis ships would be multipurpose, and the operational and life-cycle costs for such support functions as maintenance and personnel can be prorated among all the other ship's missions.
- It has outstanding political flexibility, since deployment of the ship-based TMD capability is independent of foreign control or the access to foreign bases. This advantage was highlighted by the difficulties in securing U.S. airfield rights

to deter renewed Iraqi hostilities toward Kuwait in 1996. Further, more flexible ROEs are possible if the TMD launchers are not on sovereign foreign soil.

Platform and Interceptor Options

Terminal and Pre-apogee Systems

In recognition of the TBM as a potential showstopper threat to littoral operations, the Department of the Navy several years ago decided to become an active participant in the national BMD program under the direction of the Office of the Secretary of Defense's BMDO. Following a series of studies and planning efforts supported by and coordinated with BMDO, the Navy developed a fairly conservative evolutionary TMD strategy, despite considerable pressure from some members of Congress and various strategic think tanks to emphasize long-range instead of short-range TMD and also to participate in the BMDO program for National Missile Defense (NMD) of the U.S. homeland. The panel is in general agreement with the Navy's approach, which involves the following two key elements:

1. The initial emphasis will be on terminal defense, or what the Navy calls lower-tier or area defense. The primary targets for area defense are the short-range TBMs with ranges out to 500 to 750 km. Intercept will occur in the atmosphere (less than 100-km altitude), giving rise to the term lower tier. The first-generation system will be based on the use of existing Aegis ships with modifications to the solid-propellant Standard Missile-2 (SM-2) Block IV interceptor missiles (originally designed to protect the fleet from Soviet land-based aircraft carrying sophisticated air-to-ship airbreather cruise missiles) and upgrades of the SPY radar in order to handle ballistic-missile targets in addition to airbreather threats. The primary changes to the SM-2 Block IV antiair missile will involve adding an infrared seeker, a forward-leaning proximity fuse, a faster autopilot and integrated terminal-guidance algorithm design, and a warhead more optimized for TBM targets. Although the current plans are to destroy the TBM with a blast/fragmentation warhead, a kinetic-energy kill in which the interceptor would impact the TBM is still being evaluated. High-attitude kinetic-energy kill is considered to be the surest way to protect against chemical or biological payloads. The resulting TMD interceptor, called the SM-2 Block IVA, will retain its antiair warfare (AAW) capability against primarily medium- and high-altitude cruise missiles and aircraft that venture into the interceptor's effective range. The Aegis ship will carry a mixed load of TMD/AAW and other weapons in their vertical launchers (91 missiles in VLS cells on the destroyers and 120 on the cruisers). The Initial Operational Capability for the SM-2 Block IVA system is now scheduled for around 2001. The SM-2 Block IV A has recently been designated SM-3.

Over time, as short-range TBMs become more capable, the first-generation terminal TMD system will have to be upgraded or replaced by a more advanced new system to keep pace with threat advances such as reentry vehicle maneuver, stealth, and penaids. For example, earlier warning by a third-party sensor (discussed below) of a TBM launch would allow the ship's SPY radar to focus its energy better and track a stealthy TBM at somewhat longer ranges. TMD warning of a TBM attack will give additional warning times when WMD is employed.

2. The missile was recently designated SM-3. The primary targets for this system are the longer-range TBMs with ranges of 750 to 3,500 km. Intercept will occur mainly exoatmospherically, although some theaterwide TMD alternatives can also intercept targets at high endoatmospheric altitudes. Currently the leading candidate for theaterwide TMD is the SM-2 Block IV missile rocket motor augmented with a third or kick stage and a hit-to-kill payload called the LEAP (which stands for lightweight exoatmospheric projectile). This payload is a BMDO development that has successfully integrated major advances in guidance-and-control technology into a light, compact kinetic-kill vehicle (KKV). LEAP will employ a sensitive infrared seeker with a moderate acquisition range, a compact solid-rocket divert engine for terminal/endgame corrections, and a miniaturized guidance system and processor.

Figure 5.2 illustrates the LEAP system's defensive coverage of Japan as a function of interceptor burnout velocity for interceptors launched from a ship deployed near North Korea. The SPY radar software and hardware would be upgraded to accommodate cueing from off-board/third-party surveillance sensors such as the existing defense support program (DSP) satellites and the next-generation space-based IR system (SBIRS).

A leading alternative to the LEAP system is the theater high-altitude air defense (THAAD), or a variant of the THAAD. The THAAD, now under development by the Army/BMDO for deployment by 2004, consists of solid-propellant boosters and a fairly large/heavy KKV payload. An advanced X-band surveillance and fire-control radar that is part of a quasi-mobile, ground-based THAAD battery provides command updates to the interceptor missiles in flight until the KKV's infrared seeker acquires the target. The THAAD is designed to intercept ballistic missiles exoatmospherically and also at high-endoatmospheric altitudes. The missile can be fitted into the Aegis VLS, but there are some remaining compatibility issues involving the VLS and the SPY radar. Under Navy evaluation are THAAD variants that, for example, would boost the THAAD missile with the SM-2 Block IV first-stage booster or would add a kick motor to the THAAD.

Taking advantage of THAAD as an alternative to the LEAP system would seem to be a prudent approach. However, one potentially serious problem that should be mentioned is that a hit-to-kill concept may not be robust enough against advanced ballistic missile threats that include decoys, jamming, and maneuvering nose cones. If this turns out to be the case, the Navy and BMDO will have to

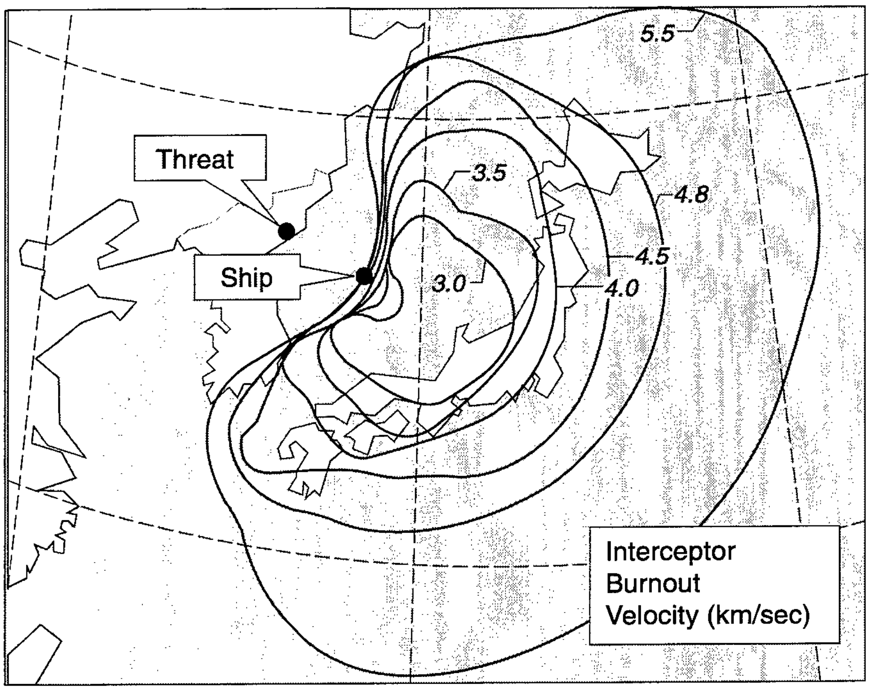

FIGURE 5.2 Navy TBMD coverage versus interceptor velocity. SOURCE: Rempt, RADM Rodney P., USN. 1996. "Navy Theater Wide Defensive Coverage Versus Interceptor Velocity," in the briefing "Theater Air Defense, The Next Generation in AAW," Office of the Chief of Naval Operations (N865), Washington, D.C., presentation to the Panel on Weapons, August 5.

rethink their layered defense approaches. So far, THAAD has not worked even against benign threats. Of course, this hit-to-kill problem is much worse in the lower atmosphere where maneuver is much easier to obtain aerodynamically.

The combination of the Navy terminal and theaterwide TMD systems plus land-based area and upper-tier systems would provide excellent defense in depth. Figure 5.3 shows the range-altitude defensive envelopes for various ship- and land-based TMD systems and breaks down the intercept zones into descent, midcourse, and ascent (pre-apogee) for the Navy's theaterwide system.

For completeness, it should be noted that the Marine Corps and the Army are in cooperation with our allies developing a land-mobile system called medium extended air defense system (MEADS) for the protection of maneuvering land forces against both TBMs and airbreathing targets. This is intended as a follow-on to the existing HAWK antiair system that is being upgraded to provide interim TBM defense. MEADS will eventually complement the Army's follow-on to the short-range PATRIOT missile, called PAC-3, and the area-defense THAAD.

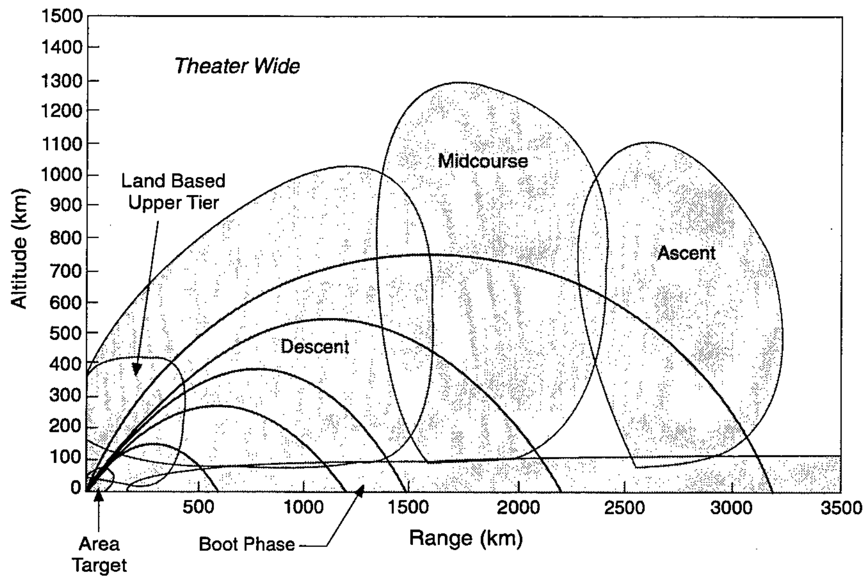

FIGURE 5.3 Defense in depth. SOURCE: Rempt, RADM Rodney P., USN. 1996. "Navy Theater Wide Defensive Coverage Versus Interceptor Velocity," in the briefing "Theater Air Defense, The Next Generation in AAW," Office of the Chief of Naval Operations (N865), Washington, D.C., presentation to the Panel on Weapons, August 5.

Other theaterwide TMD alternatives have been evaluated in recent Navy cost and operational effectiveness analysis (COEA) efforts. For example, one alternative proposed a robust KKV with sufficient guidance capability (target-acquisition range of 1,000+ km) to fly out the handoff errors from moderate-accuracy surveillance sensors such as the existing DSP satellites. One payoff of this concept is that the interceptor can be launched shortly after the TBM launch is detected. This capability, called launch-on-warning, would dramatically increase the effectiveness footprint of the interceptor and, in many cases, would result in intercepts prior to the TBM's reaching its apogee. Pre-apogee intercept can add an extra layer of defense and significantly reduce the number of surviving TBMs. Pre-apogee intercept would also negate maneuvering reentry vehicles that use the atmosphere for pulling maneuvers. Pre-apogee intercept would not necessarily negate all maneuvering reentry vehicles. For example, it might not defeat those that used small propulsive thrusters for small directional changes. Of course, preburnout intercept would negate maneuvering reentry vehicles.

Launch-on-warning usually implies a fire-and-forget capability that can pay off by freeing up the ship's radars for other missions and by permitting missile launches under emission-control (EMCON) conditions if the ship is under attack. The LEAP and THAAD concepts would also be capable of launch-on-warning

and fire-and-forget, but they would require precision targeting information from new high-accuracy, third-party surveillance sensors, such as the SBIRS.

A counter to exoatmospheric intercepts is the use of decoys, which will likely be deployed on TBMs over the next 25 to 35 years. Such responsive threats will require that the TMD interceptor and surveillance sensor system be upgraded with increasingly capable and expensive discrimination technology.

Actually, exodecoy technology could appear in operational systems at any time within the next 25 to 35 years because it would not be technically difficult to develop. However, panel members suspect that exodecoys will not be deployed until shortly after exointerceptors become operational. Although the development of exodecoys is not thought to be technically daunting, it would be relatively expensive. Most nations that are currently seen as potential adversaries do not have an infinite defense budget. A valid threat of exointerceptors must exist before someone can sell management on the importance of spending money on exodecoys as a penetration aide. If the United States does not field an operational exointerceptor for 10 to 15 years, the panel conjectures that deployment of exodecoys probably will not be seen for a few (3 to 7) years after the exointerceptor has been introduced.

Boost-phase Intercept

A countermeasure tactic that has caused considerable concern among some analysts involves the release of submunitions shortly after the TBM has completed its boost phase. If large numbers of submunitions are involved, defense is virtually impossible once the release has taken place. Early release of submunitions involves a minor engineering variant of late release, which already exists in the threat spectrum. It is projected that early-release threats could materialize within a few (3 to 7) years after the successful deployment of TMD provides a motivating factor. However, the panel's prognosis for effecting boost-phase intercept from a naval platform anytime soon is bleak. Therefore the Navy's options appear to be the following:

- Defer to the Army or Air Force for countering the threat of boost-phase decoy release. For example, the Air Force is quite serious about developing a boost-phase-intercept (BPI) system that would employ high-energy lasers deployed in large/wide-body aircraft. Although this concept appears attractive, it has many formidable technological, operational, and economic problems to overcome before it is operational. A potential problem for the Navy with this system is that the BPI laser aircraft may not always be readily available to support amphibious or other littoral operations.
- Develop a sea-based BPI system based on the use of UAVs carrying small and lightweight BPI missiles or solid-state lasers. The panel believes that since the Navy would usually be the first on the scene of a regional crisis, ships might be able to provide a timely and cost-effective platform for launching killer UAVs

to patrol areas suspected of harboring TBM launchers. Further, the panel is concerned that in scenarios such as a fast-breaking regional crisis it might be too risky to depend exclusively on the Air Force's airborne BPI laser being available in time and in force to protect a quick amphibious landing. Even a limited sea-based BPI capability could prove valuable under these circumstances in providing a vital first tier in a multi-Service and multilayered TBM defense. Without some organic defense against the TBM early-deployed submunitions that could deter naval power projection, the viability of the Navy's Forward From the Sea philosophy will become highly suspect.

BMDO several years ago pioneered a weaponized UAV BPI system, called Raptor Talon, that achieved a measure of success before encountering budget problems. The concept involved small and cheap high-altitude and long-endurance UAVs (Raptor) and moderate-speed, lightweight (less than 30 kg) interceptors (Talon). An alternative version that has been proposed by LLNL and that may be funded would replace the Raptor with the Tier 2+ UAV, or possibly Tier 3–, and replace the Talon with a somewhat more conservative interceptor concept (2.8 km/s and 120 kg). The LLNL studies indicate that the UAVs would have the range and endurance when deployed from remote land bases found in many theater areas to support most amphibious operations and, if the UAVs were deployed from ships supporting amphibious landings, the endurance could be doubled. The Tier 2+ UAV is probably too large for operations off conventional aircraft carriers, and a new ship design (without an island to leave room for the large wingspan) would be required. In the interim, it might be possible to modify the Tier 2+ UAV to accept in-air refueling from carrier-based aircraft and thereby significantly extend the UAV's patrol time over the suspected TBM areas. More detailed analysis involving plausible future scenarios is needed to establish the technical, operational, and economic viability of these naval BPI UAV alternatives relative to the Air Force's airborne laser.

Overhead airborne or space sensors or on-the-ground human intelligence (HUMINT) could be used to gather the intelligence data needed to map out suspected TBM areas that the killer UAVs would be assigned to patrol. One potential HUMINT option might be to use the proposed Marine Corps Sea Dragon teams to identify (and in some cases perhaps even destroy) the TBM launch sites out to the Marine Corps planned 400-km operational range, or possibly even beyond if long-range protective fire from the sea is available. Once the killer UAV is sent out to patrol a suspected area, the actual detection of the TBM launch would be done by the killer UAV itself or possibly a companion sensor-only UAV.

An interesting and more futuristic variation of the killer UAV concept that has been proposed would involve missiles to intercept both the TBMs in boost and also to kill the TBM launcher after they fired their first round and before they can reload (counterbattery). Conceptually this defense-offense UAV might have the on-board capability to detect the TBM in boost and to detect and identify the

launchers on the ground. Alternatively, both the counterforce and BPI sensors could be built into multimode interceptors.

The panel recognizes that significant technical and operational hurdles would have to be overcome to validate the ship-based killer UAV concept. It has already been mentioned that today's UAV technology and ship designs are not capable of achieving reliable recovery of the relatively large weaponized UAVs and that dedicated ships capable of launch and recovery of the UAVs might be needed. This type of ship may become necessary in any event if the Navy were to decide that UAVs of all types must become an essential part of tomorrow's fleet. Major advances in the UAVs will be needed to accommodate repeated launch and recovery, to increase the UAVs' payload and endurance, to reduce the vulnerability to antiair weapons, and to reduce the UAV cost to the point where expected attrition rates can be economically justified. Improvements will also be needed in the interceptors to reduce their weight, size, and unit costs so that the overall BPI UAV concept is reasonably affordable. And further work will be needed on UAV linkages to third-party target-detection and identification sensors, if this is the preferred approach, and also possibly back to the ship battle group or other theater command centers. Nevertheless, despite all these technical, ship-design and operational issues, the panel believes that over the next 25 to 35 years these problems can be solved if the perceived need for sea-based BPI is great enough.

Another Navy BPI alternative might involve a moderate-energy solid-state (diode-pumped) laser deployed on next-generation carrier fighter aircraft or UAVs. However, this is technically more difficult than the UAV/KKV combination. Nevertheless, since the Air Force is seriously investigating compact and lightweight solid-state lasers for aircraft self-defense, it is possible that technology spin-off from this effort might enable a BPI capability on future naval aircraft.

- Suppress the TBMs on the ground before they are launched. This option, although it did not prove to be successful during the Gulf War with the then-available technology, nevertheless has future potential and is discussed in another section of the study report.

Command, Control, Communications, and Intelligence

Underlying the feasibility of the Navy TMD concept is the command, control, communications, and intelligence (C^3I) system required to provide timely, accurate, and secure targeting information to the shooter on the ship. The Navy's new C^3I approach, called cooperative engagement capability (CEC), is a weapon control net that enables sensor netting for land-based and ship-based TMD and antiair warfare. The key CEC net interrelationships for the near and midterm among surveillance and warning, theater command and control, and weapon control are illustrated in Figure 5.4. Surveillance and warning will include space, airborne, and ship- and land-based sensors connected by JTIDS. The theater

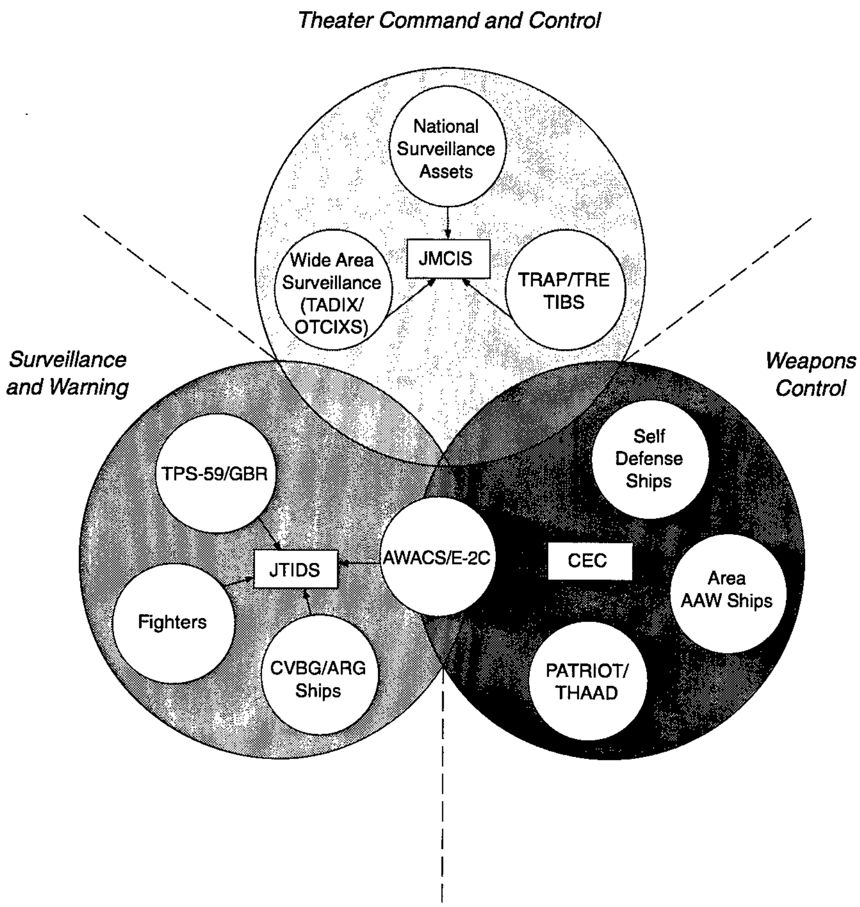

FIGURE 5.4 Theater command and control. SOURCE: Rempt, RADM Rodney P., USN. 1996. "Navy Theater Wide Defensive Coverage Versus Interceptor Velocity," in the briefing "Theater Air Defense, The Next Generation in AAW," Office of the Chief of Naval Operations (N865), Washington, D.C., presentation to the Panel on Weapons, August 5.

command-and-control elements such as national surveillance assets and tactical receive and related application (TRAP)/tactical receive equipment (TRE) and the Tactical Information Broadcast System (TIBS) will be integrated through the Joint Maritime Command Information System (JMCIS). The shooters in theater will encompass anti-TBM and antiair weapons on both land and sea.

Some of the attractive features of the CEC are that (1) it would allow a significant increase in the depth of fire and therefore the overall probability of kill (P_k); (2) it would enable engagement of targets not detected and tracked by ownship sensors; (3) it would give the combat system more time to react because of

the earlier track formation; (4) it would enable self-defense systems to maximize performance against stressing TBM cruise-missile targets; and (5) it would provide improved ability in a jamming environment. In addition, with an appropriate spectrum of sensor frequencies and with sensors distributed to gain a multiaspect view of the target, CEC at least in theory would be able to detect, classify, and track stealth targets, including LO sea-skimming antiship cruise missiles.

Over the next 35 years as the threats become more sophisticated, the first-generation sensors being linked by CEC will likely be stressed to their technological limits. CEC hardware and software will also be stressed in bandwidth and processing time. This will mandate continual upgrades and modifications in such areas as targeting reaction time (near-zero time may have to be the norm), accuracy (for improved prediction of TBM impact points and evasive maneuvers), and imaging (for better discrimination against decoys and penaids and for resolving close-spaced targets). Major improvements in weapon-control software will also be required to achieve rapid assessment and decomposition of enormous amounts of information so that the ship's defensive weapons can be quickly assigned targets in an optimum manner.

TMD Multimission Potential

Navy TMD has important multimission potential for AAW, NMD, and space control, since there is strong component commonality among all these missions. These diverse capabilities in one missile, or derivatives of a common missile, would pay off in significant cost reductions and enhanced operational flexibility when all the ships missions are taken into account.

Antiair Warfare

As noted earlier, the SM-2 Block IV short-range TMD system is designed to intercept high-altitude aircraft and cruise missiles as well as ballistic missiles. The Block IV has an effective range out to at least 200 km. Theaterwide TMD missiles will eventually have fly-out ranges of several thousand kilometers against TBMs, and designs have been proposed for building in an initial antiair capability into the TMD interceptor or allowing for upgrade to AAW later. This multimode capability would provide theaterwide AAW for the fleet and for U.S. and allied expeditionary forces as they advance inland. The long-range AAW capability could play a key role in achieving air control in future regional conflicts in view of the widespread proliferation of advanced surface-to-air and air-to-air weapons that will threaten Navy manned fighter and strike aircraft. Simultaneously, proliferation of current-generation aircraft and advanced air-to-surface weapons that can threaten ships at sea and U.S. forces ashore is also occurring. For example, it has been reported that Iran recently acquired Russian sophisticated SA-10 missiles and will likely buy the even more effective and longer-range SA-12 system.

In addition, Iran is acquiring the latest Russian attack bombers and even the long-range Backfire bomber with its sophisticated air-to-surface missiles that are able to attack both land and sea targets.

However, aircraft identification at long ranges must become more reliable before long-range AAW will be acceptable, especially if launch-and-leave interceptors are employed. Fortunately progress is now being made that should someday result in sensors and their supporting systems that are up to the task. The anticipated proliferation of low-observable aircraft technology will complicate the identification problem and will also require more capable interceptor missile-guidance systems.

National Missile Defense

The discussion of sea-based ballistic missile defense would be incomplete without some comments on NMD of the U.S. homeland against strategic ballistic missiles. To date, there has been only limited evaluation by the Navy of sea-based NMD for a number of reasons, including the political problems posed by the Antiballistic Missile Treaty with the former Soviet Union. The treaty was signed in 1972 when in the face of a large number of Soviet intercontinental ballistic missiles (ICBMs) and SLBMs, mutual assured destruction (MAD) was popularly considered to represent U.S. deterrence policy. The current White House position is that the United States should adhere to the letter of the Antiballistic Missile Treaty, especially since the strategic threat does not appear to be imminent. A majority of the Congress, on the other hand, argues that the ballistic missile threat to the homeland will materialize much sooner than has been forecast. Consequently, they want the United States to develop an NMD system on a priority basis to defend against at least limited ballistic missile attacks by Third-World adversaries and possible accidental or unauthorized launches by Russia and other nations. Some congressional leaders who believe the Antiballistic Missile Treaty of the Cold War will eventually be modified or abrogated want the Navy to participate in NMD on the basis that early intercepts possible from forward-deployed Navy ships would be essential to a layered defense approach for achieving almost-zero ballistic-missile leakage. Other reasons cited for a strong Navy NMD role are that the Navy antisubmarine capability is critical for countering the SLBM threat and also that it is always preferable to intercept missiles carrying nuclear warheads and other WMD over water instead of over U.S. cities.

The Navy's current position on NMD if directed to participate is to take an evolutionary approach with the Aegis long-range TMD system as the starting point. (It should be noted that OSD-sponsored Navy studies a number of years ago concluded that against a Soviet-type strategic threat a Trident submarine variant could provide a cost-effective and highly survivable defense of the U.S. homeland.) The C^3I for the ship NMD would be provided by one of the concepts

now being evaluated by BMDO in their ongoing Development Readiness Program conducted in compliance with the Antiballistic Missile Treaty. NMD exoatmospheric kill vehicles (EKVs) now under BMDO development could likely be adapted to the Aegis ship vertical launchers in an emergency even though the missile diameter might exceed 21 inches. Preliminary studies show that with an EKV burnout velocity of 6.0 to 7.5 km/s Navy ships on normal patrol or in transit almost anywhere in the Pacific Ocean could defend Hawaii, Alaska, and most of the western United States against a limited attack of ICBMs launched from China or North Korea. And, if the NMD ships were more optimally located in the Pacific region, almost all of the United States could be defended against the same attacks. Other studies done by the Navy and others suggest that a Navy NMD system could be more effective, cheaper, and faster to field than a land-based alternative. However, the panel believes that more detailed analysis would be required to validate these preliminary findings.

Space Control

If it was considered to be in the national interest, the Navy's long-range TMD system could be modified relatively quickly to provide a hard-kill capability against satellites that threaten U.S. military operations. Navy studies done several years ago showed that there is a strong commonality between a TMD and antisatellite missile. It was also found that in some scenarios it is advantageous to launch an antisatellite missile from certain ocean areas and that a covert submarine launch may often be desirable.

Summary

General

Navy TMD will become essential to the future of power projection as increasingly capable tactical ballistic missiles proliferate around the world. The proliferation of WMDs that will likely be delivered by the TBMs can only exacerbate the problem.

Without competent TMD, land attack from the sea will be difficult and risky. In response to the TBM threat, the Navy is currently undertaking an extensive investigation of TMD system alternatives that build on existing Aegis ships and their vertical launchers, advanced air-defense missiles, and powerful surveillance radars. The Navy's plan is for the initial development of short- to medium-range missiles for the interception of TBMs in their terminal or late midcourse phases and then later evolve to a longer-range system able to intercept TBMs in their ascent phase. Currently the Navy has no plans for a sea-based system for intercepting TBMs in their boost phase, despite the strong likelihood that future TBMs will be able to deploy large numbers of submunitions shortly after missile burnout.

TABLE 5.1 TBM Threat Evolution and TBMD Technology Needs

TBM Advances	Technology Needs
Long-range, fast TBMs with WMD	Long-range, pre-apogee interceptors (high-accuracy surveillance sensors, or very-long-range seekers)
LO TBMs, penaids, and decoys	Distributed multispectral surveillance sensors and interceptor fast/accurate discrimination
High maneuverability	Very agile interceptors with high-resolution imaging seekers/rapid-response missile controls
Submunitions deployed	
—After/just before apogee	Pre-apogee interceptors (re above)
—Just after burnout	Boost-phase interceptors (ship-based killer UAVs or manned fighters with high-energy lasers)
TBM saturation attacks	Fire-and-forget interceptors/off-board targeting
Accurate terminal seekers with ship-targeting capability	Ship quick-reaction interceptors, or high-energy lasers

TMD systems have important multimission potential that can enhance the affordability and also the operational flexibility of Navy combatant ships. The multimission possibilities include antiair warfare for air control over land and sea and defense of the U.S. homeland against limited attacks by strategic ballistic missiles.

Technology Implications

The Navy TMD effort is coordinated with and mainly funded by BMDO. As TBM quantities and capabilities increase around the world, a strong BMDO/ Navy R&D program will be essential for maintaining a competent defense. Table 5.1 summarizes some technology developments that will be needed to keep pace with likely TBM advances over the next 35 years. Technology areas that will need to be emphasized are the interceptor guidance (longer-range acquisition, improved imaging capability, lower cost and weight/size) and the C^3I (more accurate surveillance and discrimination, near-zero-time sensor-to-shooter delays). If sea-based boost-phase intercept TMD becomes desirable, new technology will be needed to enable the feasibility of advanced ship-compatible UAVs (lighter weight, longer endurance, greater payload, and more readily recoverable on Navy ships) and interceptors (much lighter and smaller, higher burnout velocities) or lasers (much more compact and lighter). The technology needed for the multiple missions that might evolve from naval TMD are similar to those required to keep pace with the future TBM threat, except that for U.S homeland BMD the required propulsion, guidance, and control and C^3I performance would be especially challenging.

Conclusions and Recommendations

The panel believes that the Navy's evolutionary TMD strategy, with short-range terminal defense as the first step, is the prudent approach in view of the significant threat uncertainties and the complex technical, operational, and cost issues involved in this new naval mission. However, before a commitment is made to any major development for the next step in the evolutionary process—a long-range pre-apogee intercept system—all reasonable alternatives should be thoroughly evaluated. The evaluation should include feasibility experiments of critical components and subsystems for the leading alternatives. Serious consideration should be given to long-range TMD interceptor concepts that also have AAW capability in view of the proliferation of advanced antiaircraft weapons and current-generation military aircraft. Because of the defense problems posed by submunitions released from a TBM shortly after it burns out, the Department of the Navy needs to undertake an extensive evaluation of boost-phase intercept options such as weaponized unmanned air vehicles deployed from Navy platforms.

Maximum support from and coordination with BMDO is strongly encouraged over the long term to ensure that initial TMD systems will keep pace with expected TBM advances and that the fiscal burden is shared among all DOD participants. The prospect of TBMs employing stealth, maneuvering reentry vehicles, penaids/decoys, and submunition warheads is of special concern as are TBMs that eventually will be able to threaten ships at sea.

In view of the growing threat of limited ballistic-missile attack of the U.S. homeland and the potentially important role sea-based defenses might play, the Navy should begin evaluating some strategic defense alternatives. The effort should take maximum advantage of BMDO developments and funding and should focus on evolving from the Navy's long-range TMD system.

CRUISE MISSILE DEFENSE

Issues and Trends in Cruise Missile Defense

The Navy's baseline CMD system consists of the Aegis SPY-1 radar and the SM-2 BLK, which provide an effective area defense against current and advanced cruise missiles. Point defense for individual ships without Aegis/SM-2 capabilities is provided by the close-in weapon system (CIWS), which consists of the 20-mm high-rate-of-fire Vulcan Phalanx gun. The 5-in. rolling airframe missile and the Sea Sparrow missile system are also used on some ships to provide additional point and local area defense.

Although the Aegis SPY-1/SM-2 system is an extremely competent system, there is reason for concern about its performance against postulated future cruise-missile threats. Many analyses indicate that the performance of the SPY-1/SM-2 will degrade if future threats have the following:

- A sea-skimming trajectory that allows it to fly under the beam of the Aegis radar,
- A nose on RCS that is many decibels below the target strength the system was designed to counter,
- An ability to pull high-*g* terminal maneuvers, and
- Attacks based on multiple close missile arrivals ("saturation").

Missile designers who are attempting to produce antiship cruise missiles that could defeat the SPY-1/SM-2 defense are certainly aware of the limitations of these systems. As a result there is a worldwide trend towards the production of the following:

- Faster/more agile (maneuvering) missiles,
- Low-observable missiles with sharply reduced RCS and IR signatures, and
- Sea-skimming missiles with trajectories as low as 3 meters above the ocean surface, which sharply limit the range to the radar horizon and consequently the reaction time available to the defensive system.

When these missile attributes are taken in conjunction with the possibility that future adversaries may also use saturation tactics to defeat the SPY-1/SM-2 defense, there is reason for concern. The Navy is acutely aware of the potential problem and has long supported a number of programs that are oriented to the achievement of a more robust defense. These programs have concentrated on the development of the following:

- Means to negate the impact of reduced nose-on RCS,
- An improved horizon-search radar and look-down radars,
- Development of IRST systems,
- Improved speed and agility in the defensive missile,
- Multiple-platform internetted sensors, and
- A robust terminal defense system.

The search for a robust terminal defense system has been under way since World War II. The future prospects for terminal defense concepts that are, and have been, under consideration are discussed in the section under CMD.

Through the years the Navy has achieved a steady improvement in the performance of its defensive missiles and has upgraded the SM-2 BLK III and developed the BLK IV and the BLK IV-A. Further improvements must await some of the advances in propellant technology discussed in the section on sensors.

Although the performance of the Navy's horizon-search radars has improved, they are still limited by the range of the radar horizon, which depending on missile altitude and radar antenna height is likely to be between 10 and 20 nautical miles. A cruise missile traveling at a high subsonic speed can transverse such distances in times of between 1 and 2 minutes. That implies that when

defending against a high-subsonic speed sea-skimming cruise missile the system must detect the missile, establish the missile's track and launch an intercept weapon within 1 or 2 minutes after first possible detection at the horizon. Actually the available time for the engagement of the threat missile is further constrained because it is desirable to destroy the missile when it is more than 5 kilometers from the ship.

In principle, the detection of sea-skimming missiles does not need to be accomplished solely by a horizon-search radar. If the clutter problem can be solved satisfactorily, an elevated look-down radar can be used to detect the missile against the background of the ocean's surface. Although the Navy has developed a surveillance radar with excellent capabilities for the rejection of sea clutter, the development of an airborne radar dedicated exclusively to the task of detecting a sea-skimming missile has not occurred and is not currently programmed by the Navy.

Fortunately, for reasons of aerodynamic efficiency, few long-range cruise missiles have trajectories that cause them to fly their entire track at extremely low altitudes. This implies that for much of their transit, the missiles will be at altitudes that place them within the beams of Aegis or other radars. The probability of long-range detection is a function of many factors such as available beam power, target aspect, target RCS as a function of aspect angle, radar processing gain, the local clutter environment, and the presence of jamming and decoys. Consequently the major thrust of the Navy's effort to upgrade its defensive capabilities has been to improve the detection range of its sensors. These efforts have culminated in the development of upgrades to the SPY-1 and the development of the CEC which has proven to be remarkably successful. The attributes of this system and its project future capabilities are discussed in the following section on networked sensors.

Joint Operations Air Defense

The Navy will conduct joint operations in the future utilizing assets such as AWACS, JSTARS, and the airborne laser (ABL). A major concern is the defense of these important platforms against a variety of surface-to-air missiles (SAMs) and air-to-air missiles (AAMs). SAMs with 100-nautical-mile ranges are already available and hypersonic cruise missiles for attack of air targets are under development. Although some protection will be provided by combat air patrol (CAP) against aircraft launch platforms and the ABL has some self-defense capability, the missile threats are a serious problem for these expensive, high-visibility systems.

If CAP does not prevent AAM launch, for example, only countermeasures offer protection for JSTARS and AWACS. In the case of ABL, if a missile attack is coordinated with a ballistic missile launch, ABL will have to choose between self-defense and carrying out its primary mission, which is booster destruction, during a narrow launch window.

The panel suggests that the Navy study the development of an air-defense system to protect these high-visibility platforms against missile attack by extending the CEC defense umbrella to include SAMs, AAMs, and even antiair cruise missiles (CMs) that could be targeted against the AWACS, JSTARS, and ABL.

The Aegis/CEC system is being developed to engage CMs targeted against ships and to provide defense against theater and, perhaps, strategic ballistic missiles. This is already a complicated defense concept and the rules of engagement are in evolution. However, it should be possible to extend the defense volume to interdict missiles targeted against major airborne command and control and weapon assets. The signature and speed characteristics of these threats are within the envelope of those being considered for fleet defense against aircraft, CMs, and TBMs. It remains to be determined whether a deployment strategy can be developed whereby fleet defense, TBM defense, and defense of major air assets can be accomplished. It is possible, moreover, that an AAM, either launched by the CAP or by the large air platforms, will offer a competitive advantage for missile defense. This should be traded off against a CEC extension in a study. Clearly, if there is no defense provided by the Navy, it is improbable that these important systems will find full use in proposed operations.

Networked Sensors

The general principles of a networked sensor system are discussed in Chapter 4, "Air-to-Air Weapons," in the section titled "Major Issues and Drivers." The principle of operation of a networked sensor system is the same for CMD as for air-to-air combat. If the outputs of a number of dispersed monostatic radars, all of which illuminate a common target, can be provided to a central processor, the probability is high that detections can be made and tracks can be formed because some individual radar or radars in the network will observe the target from a bearing that has a large retroreflection of incident electromagnetic energy.

If a network of sensors can establish the target's track, a weapon can be released from the ship in the best position to engage the target. With the CEC system there is no requirement that the ship that launches the defensive missile is the ship that had a sensor that detected and tracked the target.

The introduction of CEC technology will provide the Navy with a robust CMD capability that should be available many years into the future. Unfortunately there are now and probably will continue to be limitations to the performance of a CEC system. The two principal threats to the future effectiveness of the CEC system are as follows:

- The development of targets that have all-aspect stealth, and
- The existence of situations in littoral engagements where, because of limitations imposed by the enemy's air defenses and the shore line, the possibility of positioning monostatic radars far enough forward and at sufficiently dispersed bearings to ensure that at least one radar be in a position to detect target glints is

precluded. In addition, ships operating close to enemy shores are especially vulnerable to preemptive attacks by short-range ASMs.

Although the panel is aware that it is feasible to produce missiles and aircraft that have all-aspect stealth at some set of radar frequencies, the panel is doubtful that all-aspect, all-frequency stealth will become a commonplace technology in the immediate future. In the panel's view the greatest short-term threat to CEC effectiveness will arise in situations where for local operational reasons radars cannot be employed to allow the full power of the CEC system to be realized.

Despite the evident success of the CEC approach, the panel suggests that the Navy would be prudent to develop alternate techniques to negate LO targets. Among the approaches that might be explored would be the development of a network based on the use of multistatic as opposed to monostatic radars. The basis for such an approach is discussed in "Major Issues and Drivers" in Chapter 4.

The panel believes it would be feasible, albeit difficult, to implement such a concept. There have been many concepts advanced over the last 50 to 60 years for multistatic radar operation. Concepts that involved beam and pulse chasing have proven to be infeasible; however, multistatic radars (e.g., the Distant Early Warning line and the Navy Space Surveillance system) have been built and operated.

Currently, the most promising concept is based on having a sensor that is not co-located with the transmitter but is located along an LOS path to the transmitter, so as to permit the detection of both the outgoing pulse and the target reflected pulse. A correlation processor is used to determine the time difference of arrival between the direct and target reflected paths. If the receiver is not directional, and if both the transmitter and receiver locations are known by the processing computer, then the target will be located on an ellipse whose foci are at the location of the transmitter and receiver. If the receiver has directional reception capabilities, or if multiple receivers are employed, then the target can be located along a specific segment of the ellipse.

The early radars of the late 1920s and 1930s were all multistatic. In 1936 the duplexer, which permitted monostatic operation of radar, was invented. From that time on, virtually every radar was monostatic. Sixty years later almost all of the early problems associated with multistatic operation have been solved. Technology to provide accurate locations of sources and receivers, accurate clocks, correlation processors, appropriate wave forms, and so on, is available. The principal remaining problems relate to clutter rejection and computational capacity (which should disappear in the very near future).

The processor node would need to be supplied with the time of each transmission, and replicas of the transmitted waveforms, in addition to precise information relative to the location and velocity of all transmitters and receivers. An extremely wideband data link would be necessary to support the operation of the network.

Assessing the technology required to build such a sensor system, the panel has concluded that it should be feasible to build such a system in the near future.

The panel believes that the use of a network of sensors such as those employed in the CEC system will greatly enhance the Navy's ability to defend against attacks by first-generation stealth cruise missiles. If the threat becomes intractable because of a future proliferation of all-aspect, all-frequency LO, then the Navy will probably need to deploy a networked multistatic detection system. Such a networked multistatic system will be expensive to develop and will stress the capability of current and near-term technology.

Projected Future Evolution of CMD Weapons

James F. McEachron[1] presents the best general summary of the problems faced by the designer of ASMs. Although the article is written from the perspective of the designer of offensive weapons, the precepts and analyses contained in that article may be used to provide guidance to consideration of the future evolution of CMD weapons and weapon systems. The general summary of that article, quoted here in total because the panel believes that it represents the best general summary of the CMD situation, is as follows:

- High-altitude defense penetration by an ASM requires either extreme stealth, extreme speed, or a combination of the two.
- Very low altitude flight results in high ASM survivability against RF-guided SAMs regardless of ASM speed.
- A subsonic ASM will likely have higher survivability than the supersonic ASM against IR-guided SAMs.
- The high-IR signature of supersonic ASMs allows targets to be cued at long ranges during EMCON.
- Accurately directed (radar, laser radar, infrared) point-defense guns with unguided projectiles can defeat nonmaneuvering subsonic and supersonic ASMs.
- Salvoes of both subsonic and supersonic ASMs can defeat point-defense guns using simultaneous times on target.

RF-guided Surface-to-air Missiles SM-X (BLK-Y)

To understand the panel's assumptions about the expected evolution of RF-guided SAMs, it is useful first to review the strengths and weaknesses of existing CMD systems.

Radar-guided SAMs provide the longest-range protection of surface ships and are typically associated with sophisticated fire-control systems mounted on

[1]McEachron, James F. 1997. "Subsonic and Supersonic Anti-ship Missiles: An Effectiveness and Utility Comparison," *Naval Engineers Journal*, 109(1):57-73, January.

larger combatants. In a classic notional engagement with an ASM, the ASM would first be detected and identified as a potential target by an acquisition radar designed to transfer or hand off the ASM position to a fire-control radar that keeps track of the ASM and often performs the missile-guidance or illumination function. Once the fire-control radar has the ASM in track, a SAM is launched and is guided to the target by command from the radar or by a semiactive seeker in the SAM that homes on an illumination signal from the radar. The SAM fuse senses the proximity of the target and detonates the SAM warhead.

In a more modern system that employs the CEC system, there is no requirement that the acquisition radar, the fire-control radar, or the SAM launcher be on the same ship or even be on a ship.

Unfortunately, significant inherent reaction-time delays are incurred between the acquisition-track process and the track-launch process. In addition, all SAMs have a minimum range inside of which they cannot reliably intercept a target. Obviously, the detection ranges of the SAM radars, the reaction times, the dead-zone distances, the SAM fly-out velocities, system accuracy, fusing capability, and warhead size all affect the ultimate effectiveness of the defense system. When the ASM travels at supersonic speeds, the defense timeline will be compressed and the result will be fewer intercept opportunities.

A detailed discussion of the capabilities of present and projected Navy CMD systems is beyond the scope of this report. However, some important tradeoffs can be illustrated if we consider the performance of a hypothetical RF-guided SAM system against generic ASM threats. For purposes of illustrating the strengths and weaknesses of contemporary CMD systems we shall assume a defensive system with the following attributes:

- Acquisition radar range of 100 nautical miles versus 1-m^2 target;
- Track radar range of 50 nautical miles versus 1-m^2 target;
- Time delays of 10 or 20 seconds acquisition to track, and 10 or 20 seconds track to SAM launch;
- Dead zone of 2 nautical miles;
- SAM velocity sufficient to reach edge of dead zone in 6 seconds and Mach 3 average over longer ranges;
- Accuracy of 5-meter miss distance (one sigma); and
- Radar antenna height of 18 meters.

The assumed height of a radar antenna establishes the radar horizon. For our choice of an antenna height of 18 meters, the radar horizon will be only 26.7 km against an incoming missile that flies from launch to target at an altitude of 5 meters. This represents one of the most serious limitations of a CMD system that is not augmented with CEC. Without CEC, the ship's first detection opportunity will occur when the missile crosses the radar horizon.

On the other hand, if the ASM is designed to fly a predominantly high-altitude trajectory (as most ramjet-powered supersonic missiles must do to achieve

a significant standoff range, then depending on the altitude of the missile), first detection could take place soon after launch at ranges exceeding 160 km. In such circumstances, our hypothetical CMD system could achieve four shoot-look-shoot opportunities against a Mach 2 ASM prior to the time the ASM reaches the dead zone of the defensive SAM.

Although the P_k of each attempted SAM intercept is complicated to compute, even a small P_k, when compounded by multiple intercepts, will improve the performance of the defense significantly. If the ASM is designed to fly faster, at say Mach 3, the opportunities for interception will be reduced but not eliminated.

The performance of the defensive system will be degraded if the radar cross section (RCS) of the ASM is reduced enough to avoid detections and intercepts prior to reaching the SAM's dead zone. To defeat the tracking radar of our hypothetical CMD system which is assumed to have a 20-second reaction time, a Mach-2 ASM would have to have a nose-on RCS of –27 dBsm (decibels relative to a square meter). If the CMD system reaction time was 10 seconds, the nose-on ASM RCS must be reduced to –34 dBsm (for comparison, the median X-band RCS of a typical missile-like shape is about 0 dBsm, a pigeon is –20 dBsm, and a locust is between –30 and –40 dBsm.[2] The requirements for a subsonic high-altitude ASM are more severe and would require a nose-on RCS lower than –40 dBsm.

Thus, high-altitude defense penetration by an ASM will require extreme stealth, extreme speed, or some combination of the two. In fairness to the problems of the designer of an ASM, the cross-section reductions given above will be less demanding if the missile attack is supported by high-power standoff jammers or if the missile carries decoys or other countermeasures that will degrade the performance of the defensive radars or defensive SAMs.

The speed and RCS requirements to deny intercept at low altitude are less severe. Since detection is limited to the horizon, no matter how high the RCS, there is an ASM speed above which, for a given CMD system delay time, SAM intercepts will be completely denied regardless of the RCS of the attacking ASM. For our hypothetical CMD system with a baseline 20-second time delay, an ASM flying from over the horizon directly to the defending ship at speeds greater than Mach 1.5 would never be intercepted. Here, supersonic speed shows a clear advantage. An improved CMD system with a 10-second reaction time would force the ASM speed requirement above Mach 2.6. Again, we see that in order to deny ASM intercept by a modern CMD system, extremely high speeds, low RCS, or a combination of both will be needed.

Having discussed this tradeoff, it is important to recognize that intercept denial is not the only means of defeating a CMD system. Another technique that could be used is to cause the SAM to have a low single-shot probability of kill (P_k^{ss}) given an intercept. The P_k^{ss} of semiactive RF SAMs against low-altitude targets is inherently

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[2]Nathanson, E.F. 1991. *Radar Design Principles,* 2nd ed., McGraw-Hill, Inc., New York, pp. 171-184.

limited by the capability of the SAM seekers to detect and track in clutter. The P_k^{ss} may also be degraded by maneuver-induced miss distances or by low-altitude-induced prefunctioning of the SAM's fuse by the sea surface.

Most radar-guided SAMs use a radio-frequency fuse that operates like a tiny radar. These fuses do not work well at very low altitudes because they have difficulty in discriminating between the real ASM target and the clutter return from the sea surface.

The problem may be illustrated by considering a situation where an ASM is flying at a fixed altitude above the sea surface and is intercepted by a SAM. The SAM's RF fuse beam extends outward at some angle and is triggered when a target is detected inside the absolute cutoff range. If this target is really the sea surface, then the SAM warhead will be detonated before the SAM reaches the ASM. Through the use of this geometry and a hypothetical fuse, the probability of fusing on the ASM can be determined. If we assume that the target ASM flies at an altitude of 5 meters above the ocean surface, and if we select the following representative parameters—fuse-cone half angle: 60 degrees; SAM miss distance: 5 meters (1 sigma); SAM dive angle: 10 degrees; fuse range cutoff: 20 meters—calculations would show that the SAM fuse is nearly always defeated. As the ASM flies higher, the computed operation of this fuse will become more reliable because the fuse's ability to distinguish the ASM from sea clutter returns will improve. The translation of this fusing example into a P_k^{ss} would be a complex process, but for purposes of this report, we may assume that fuse function means a kill and prefunction means no kill.

The Navy's current CMD system (Aegis radar and SM-2) has evolved continuously over the last several decades. Programs and developments are under way that address the problems discussed in the foregoing paragraphs. As a result, the panel believes that 25 to 35 years into the future, the performance of the Navy's CMD system will be enhanced significantly by the insertion of the following technologies:

- Expanded and enhanced CEC system;
- Dual-mode seekers (semiactive radar augmented with a two-color, mid-wavelength IR, and UV);
- Reduction of system delay time from acquisition to weapon launch;
- More agile missile with improved flight control to provide high P_k^{ss}; and
- Improved fuse performance based on use of IR angle data and better clutter rejection through new forward-looking RF detector.

In effect, the threat of reduced-RCS missiles should be negated by the expanded use of CEC techniques and dual-mode guidance. Higher-speed threats will be negated by the introduction of more energetic boosters and more agile airframes, and low-altitude fuse problems will to some extent be alleviated by the introduction of combined IR and forward-looking narrow-cone fuse.

Infrared-guided Surface-to-air Missiles

IR-guided SAMs have been in worldwide use for many years. They tend to be deployed on small combatants and generally have capabilities that are much shorter range than those of radar-guided SAMs. Typically they employ electro-optical fuses which function at low altitude. The small detection range of an optical fuse is acceptable on an IR-guided SAM because its terminal accuracy is inherently higher than that of RF-guided SAMs. Generally an IR SAM system must be cued by a long-range sensor on the defending ship. In earlier versions of IR SAM designs, it was physically necessary to aim the weapon toward the incoming ASM so that the seeker could achieve lock-on. Modern IR SAMs are generally designed to accept some form of midcourse guidance from a shipboard sensor and have tail-control fins that allow it to be steered toward its target.

James F. McEachron[3] provides computations of the lock-on ranges that can be achieved by an IR SAM against subsonic Mach-0.8 turbojet ASMs and against Mach-2 ASMs assuming typical sensor performance in the 3- to 5-μm band. There will be great variability in range because of missile operating factors and weather conditions. The contrast signature for a Mach-0.8 subsonic turbojet-powered missile is near zero, since the background radiance is about the same as the target radiance. Even if the background is ignored, the maximum lock-on range that will be achieved by an IR SAM against a Mach-0.8 turbojet ASM will only be about 1.9 km. Against a Mach-2 missile, with its contrast signature of about 20 W/sr, the IR seeker can achieve a lock-on range of 5.5 km. If the supersonic missile is maneuvering and produces a contrast signature of about 50 W/sr, the lock-on range will be about 6.8 km.

As with RF-guided SAMs, there is a relationship between the ASM IR signature and the speed needed to deny an intercept opportunity to the IR SAM. This relationship can be derived from the IR seeker lock-on equation and the kinematic characteristics of the SAM. Using the kinematic characteristics of currently operational IR SAMs, one finds that a Mach-2 ASM must have an IR signature less than 10 W/sr to avoid intercept. Since the signature of Mach-2 ASMs is likely to be in the vicinity of 20 to 50 W/sr, they generally can be intercepted by existing IR SAMs if the SAMs are launched in time. On the other hand, a Mach-0.8 ASM can avoid interception if its contrast signature is less than 1 W/sr. Typically, even if background effects are ignored, such an ASM has nose-on signature that is less than 1 W/sr. Thus, subsonic ASMs are more survivable against current IR SAMs than are supersonic ASMs.

The foregoing considerations will obviously drive the evolution of future IR SAMs. The first priority will be to design missiles that can be command guided to their target lock-on range. This implies that future IR SAMs will be provided

[3]McEachron, James F. 1997. "Subsonic and Supersonic Anti-ship Missiles: An Effectiveness and Utility Comparison," *Naval Engineers Journal*, 109(1):57-73, January.

with either or both dual-mode semiactive radar guidance and midcourse command guidance.

Programs are under way to improve the kinematics of existing IR SAMs by the addition of booster rockets to increase their range and velocity. To avoid the need to aim an IR SAM by slewing its launcher, the missile will evolve into an agile 50-*g* tail-controlled weapon that can steer itself to target closure based on either dual-mode guidance or command guidance.

Current plans include launch compatibility with the Mk-41 VLS launcher. Four of the evolved Sea Sparrow missiles (ESSMs) will be contained within subcells of a single Mk-41 cell. Finally, the warmup time of the ESSM will be reduced to a few seconds so that it can respond to detections by shipboard or networked sensors. The panel believes that its programmed future capabilities for rapid launch, improved sensors and command guidance, and greatly improved kinematic characteristics should certainly improve its performance against sea-skimming subsonic ASMs.

Point-defense Gun Systems

A point-defense gun system consists of a tracking device or combination of devices (e.g., radar, IR, and television), a fire-control computer, and a high-rate-of-fire gun. The tracking device provides accurate target position (and sometimes velocity) to the fire-control computer that points the gun. The projectiles may range in size from 20 mm to 40 mm and destroy the target antiship missile by direct hit or, in the case of larger projectiles, by proximity detonation. Some gun systems have an autonomous acquisition capability, whereas others rely on an external ship sensor to provide the initial cueing of the tracking sensor.

The survivability of an ASM against point-defense guns is primarily affected by three factors: (1) the tracking accuracy of the gun-pointing sensor, (2) the ballistic dispersion of the projectiles, and (3) the vulnerability of the SAM to a projectile given a *hit*. The panel did not address proximity-fused projectiles and medium-caliber guns (57 mm, 76 mm, and larger) which may have only limited anti-ASM capability, since they generally do not have high enough rates of fire to obtain high confidence of a hit.

The driving factors that determine the effectiveness of a point-defense weapon are incorporated into the well-known Carlton damage equation. The equation expresses the probability of any one projectile hitting a target as a function of the mean tracking-system error at the target, the ballistic dispersion, and the presented area of the target.

A generic gun (e.g., the U.S. Navy Close-In Weapon System [CIWS]) can have approximate parameters defined below:

- Rate of fire: 6,000 rounds per minute;
- Mean tracking-system error: 2 milliradians (1 sigma);

- Ballistic dispersion: 2 milliradians (1 sigma);
- Open-fire range: 2,500 meters; and
- Minimum range: 140 meters.

A generic ASM may be taken to be 36 cm in diameter and 457 cm long. Typically, a subsonic ASM cruises at a 5-degree angle of attack (AOA) whereas a Mach-2 ASM typically cruises at a 1-degree AOA. If we assume that the ASM is flying directly at the gun system, the subsonic variant will have a presented area (A_p) of 0.23 square meters and the supersonic variant will have an A_p of 0.13 square meters. Thus, if the two variants are identical in size as we have assumed here, then the supersonic missile has an immediate advantage of having only 60 percent of the subsonic A_p simply due to AOA. Generally this relationship cannot be expected to hold true because for the same missile standoff range, the supersonic variant is inevitably larger.

A simplistic analysis using the Carlton equation shows that an incoming Mach-0.8 ASM would be expected to receive one hit by 800 meters range-to-go and eight hits into minimum range. A Mach-2 ASM would receive one hit by 250 meters and two hits into minimum range. Obviously, in this case, a supersonic ASM has better performance because its speed limits the number of projectiles encountered.

Maneuvers are sometimes used in an attempt to achieve a further decrease in the number of hits. Potentially, a maneuver decreases the pointing accuracy of the gun by changing the ASM position too rapidly for the gun's fire-control computer to predict the position of the ASM at impact. However, all aerodynamic maneuvers increase the AOA, and A_p and will actually decrease survivability in cases where the maneuver does not degrade the gun's pointing error heavily. For a typical ASM just to recover the loss in survivability because of increased A_p, any maneuvers are counterproductive to ASM survival unless they degrade the pointing error to above 3 milliradians. Whether this is possible or not depends on the sophistication of the gun's fire-control algorithms and the timing of the maneuver. The closed-loop spotting of the CIWS is especially vulnerable to ASM maneuvers.

The number of hits does not necessarily translate directly into ASM kill. Generally, the P_k achieved against a subsonic ASM reaches a higher level at longer ranges than a supersonic ASM. A one-shot kill criterion may be more applicable to the supersonic missile than the subsonic for several reasons. First, the higher speed results in a higher projectile impact velocity, which ensures penetration of even armored warhead cases and coupling of more energy into the target. A 1,000-m/s projectile, for example, impacts the Mach-2 vehicle with 78 percent more energy than the Mach-0.8 vehicle. Also, the Mach-2 airloads are six times as high as at Mach 0.8, resulting in greater vulnerability to projectile-induced aerodynamic damage.

No matter how capable a defensive gun system may be, existing and pro-

jected types can only engage one target at a time. A Mach-0.8 ASM traverses the engagement zone postulated here in 9 seconds, the Mach-2 ASM in 3.6 seconds. The gun will need a substantial fraction of this time for a single kill. In addition to the time required to engage each ASM in a multimissile attack, the gun system takes time to switch targets—slew to the new bearing, track, lock on, and obtain a fire-control solution. Two or more ASMs arriving at nearly the same time will virtually guarantee that at least one will penetrate the defense. The supersonic missile offers better performance in this regard, but both subsonic and supersonic will be effective.

Based on the previous comments, the panel concluded that there are limited possibilities for improvements in the lethality of existing gun systems employing unguided projectiles. In principle, improved performance might result from the following:

- Larger-caliber weapons,
- Higher rates of fire,
- Increased engagement range,
- Decreased dispersion of rounds,
- Faster slew time, and
- Faster computation rates.

An examination of the first three suggestions leads to the conclusion that they would result only in some marginal improvement in performance at the cost of a significant increase in weight and shipboard footprint. All require larger and heavier gun barrels, larger magazines, and larger propellant charges. Most examinations of these approaches have led to the conclusion that the performance gains were not worth the costs associated with weapon growth.

Efforts have been under way for many years to decrease the dispersion of rounds. For a number of reasons associated with exterior and interior ballistics, progress has been slow and the prognosis is that progress in this area will continue to be slow. The panel is not optimistic that much progress will be achieved in the reduction of the dispersion of rounds.

Somewhat faster times for gun slewing may be achieved, but again the improvement is likely to be marginal. There is a limit to how rapidly and precisely a large mass can be moved. The slew rate of the present CIWS is already remarkably fast.

One area where progress can be made is in speed of computation. The present CIWS computer is quite fast and is not the factor that limits system performance.

The panel believes that overall the performance of the CIWS is impressive and that further improvements will be slow to be realized. If enhanced performance is required, the panel believes that an entirely new gun concept will be required. An example of this approach is discussed in the following section, "Small, High-speed,

Gun-launched Interceptors (Firebox Concept)," where the concept is to build a more agile and larger projectile rather than a more agile and larger gun.

Small, High-speed, Gun-launched Interceptors (FireBox Concept)

The kinematics of interception of a maneuverable missile generally requires the interceptor to have a significant speed and maneuverability advantage relative to its target. Such an advantage could be achieved against a subsonic sea-skimming missile if the interceptor were a small, extremely agile weapon that was capable of achieving fly-out speeds of Mach 3 with 50-*g* maneuverability and was guided to its target by semiactive guidance.

The so-called FireBox concept envisages the use of a trainable deck-mounted box gun launcher that contains a number of small (60-mm diameter) rocket-sustained weapons that can sustain Mach 3 to a range of 5 km. In this concept, guidance is accomplished with a W-band shipboard illuminator and a W-band munitionborne seeker.

The FireBox gun-launched, hit-to-kill weapon concept is an approach that emerged from ONR initiatives in lightweight gun design and in low-cost miniature RF terminal guidance. The result is a conceptual weapon system package that should be about the same size and weight as the current CIWS. FireBox should be able to provide all-weather defense against high-speed, highly maneuverable, low-flying threats accompanied with deceptive jamming. A depth of fire of 2 should be attainable against these threats, thereby achieving an acceptable hard-kill-based probability of raid annihilation.

Weapon intercepts that provide reliable catastrophic kill out to 3 nautical miles and as close as 0.5 nautical miles should be achievable with this gun weapon concept. The battle space of current missile systems, such as the rolling airframe missile, is limited by inadequate low-speed maneuverability and low-boost acceleration. The combination of horizon-limited surveillance detection range and limited boost acceleration limits both minimum intercept range and maximum intercept range.

The proposed 60-mm FireBox projectile weighs 13 lb and includes a 2.5-lb penetrating mass, a sustain motor, a low-cost miniature IMU based on micromachine accelerometer technology, a low-cost semiactive millimeterwave seeker, and a wideband data link. The projectile initially uses command midcourse guidance and then transitions to terminal guidance.

The airframe design employs a canard-plus-tail configuration in which control would be provided by the canards. The projectile is extremely agile with an airframe time constant of 50 ms, which is needed to support hit-to-kill guidance accuracies (CEP < 0.5 ft).

Catastrophic kill can be achieved by direct impact on the threat with collision energy of 0.85 megajoules against even a subsonic sea skimmer; this is 16 times the impact energy achieved by the 20-mm CIWS round and 8 times the typical

cumulative impact energy of missile-fragmenting warheads. Against the projected supersonic sea skimmer, the impact energy, 2 megajoules, is even greater.

The unique technology in the projectile is the low-cost RF terminal guidance which should be able to support hit-to-kill guidance accuracies in the presence of low-altitude sea reflections (multipath and clutter), target glint, and deceptive threat countermeasures while fitting in a 60-mm by 240-mm package. The seeker architecture is remote semiactive guidance similar to the Patriot seeker. The antenna, antenna-beam-steering unit, and receiver are on the projectile, whereas most signal processing is performed on the ship. The result is that normally expensive guidance component functions are performed on ship processors and are not expended. Seeker cost is then comparable to command guidance without the command-guidance system limitations of limited intercept range, limited adverse-weather performance, and limited capability against multiple threats.

The key element on board the weapon will be the low-cost, electronically steered antenna which is necessary to avoid expensive gun hardening while providing rapid beam steering. Two alternative low-cost, electronic-beam-steering antennas have been prototyped. The first antenna is a dual orthogonal linear array. This W-band, semiactive array has 1.5-GHz bandwidth with 32 individually gain- and phase-controlled elements in each of the two linear arrays. This antenna is the first active gain-and phase-controlled electronically steered array and will steer the 3.2° beam over 30° off axis.

Each linear array determines the target angle in one axis with monopulse processing. Together, both linear arrays provide the two-dimensional position of the target. The second W-band antenna is a hybrid design employing a Cassegrain configuration of a fully populated reflective array and a quasi-optical receiver. The quasi-optical receiver supports monopulse processing, has greater than 1 GHz of bandwidth, and supports a fully integrated receiver design on a single substrate utilizing a state-of-the-art, low-loss downconverter. The fully populated array employs approximately 500 elements, each with 8-bit phase shifters utilizing integrated circuit technology.

In the current state of the art, RF-guidance accuracy is limited by multipath and target glint. Multipath is caused by electromagnetic scattering that bounces off the target and then bounces off the sea surface before being sensed by the seeker, resulting in a variable electromagnetic sum of the scattered and direct RF signals and causing substantial errors in angle measurement. Glint is caused by multiple RF scatterers on the target, similarly degrading angle-measurement accuracy. Guidance accuracy in the presence of glint, multipath, and countermeasures is achieved using wide-bandwidth RF waveforms capable of extreme range resolution (resolution of 7.6 cm) that, when coupled with the airframe agility, is sufficient to resolve multipath and glint. In FY 1996, wide-bandwidth, MMW scattering measurements were conducted on several full-scale missiles verifying for the first time computational scattering predictions and validating the use of

range resolution to resolve target glint. Both antenna configurations provide the wide bandwidth needed for high-range-resolution waveforms.

Achieving the desired depth of fire while satisfying system size and weight goals will require the development of a lightweight gun capable of achieving 4 megajoules of muzzle energy (driven by fly-out speed requirements) and a 3-Hz firing rate capable of launching long-length 60-mm guided projectiles. The muzzle energy and system weight goal represent a need for a 200 percent increase in launch energy/gun weight over current state-of-the-art guns.

The FireBox gun design satisfies these launch and barrel requirements by the adoption of a filament wound carbon composite designed to satisfy the strength, weight, and firing-rate requirements. The significant new technology is represented by the ability to deliver high-composite strength in the thick-wall design that is required to satisfy the gun strength and stiffness.

FireBox is a multibarrel super-caliber box design in which each barrel is fired only once per AAW engagement. This minimizes barrel heating, which is a particular issue with composites, as composites must stay below their glass transition temperature (350 °F) to maintain strength. This gun concept eliminates the normal sequential feed mechanisms with in-chamber projectile storage and electronic round selection and firing and thus results in both great reliability and a high rate of fire. All barrels can be loaded or unloaded at one time. The ammunition feed system can upload or download the entire gun in a single operation. The box design groups all barrels into a single mass to dampen recoiling motion. The gun consists of 9 to 16 127-mm barrels, which exceeds the requirement of two separate multitarget engagements. Each barrel weighs 350 lb.

The weapon control provides midcourse-guidance commands, two channels of high-power target illumination to support semiactive guidance, projectile terminal-guidance signal processing, and rapid-kill assessment. The high-power MMW illuminator would utilize Gyro-Klystron and Gyro-Twystron high-power amplifiers, funded and developed by ONR. Kill assessment is based on direct detection of target impact, resulting in rapid kill assessment (under 1 second).

The panel believes that the development of a FireBox system is basically a system-integration problem. However, the panel is not able to assess how challenging or how expensive such a development would be, nor can the panel assess how well such a weapon would perform under various conditions of encounter. Nevertheless, the concept is intriguing and a limited number of weapons could be produced so that their performance could be established and the requirements for other components of the FireBox system could be defined more accurately.

Directed-energy Weapons

Directed-energy weapons (DEWs) are generally understood to include high-power microwave (HPM) devices, high-power lasers, and charged-particle-beam weapons. Because they have weapon applications beyond those limited to CMD,

a more extensive discussion of laser weapons is presented in the section below entitled "Defense Against Chemical and Biological Attack." Particle-beam weapons are no longer funded by DOD and are not discussed in this report.

High-power Lasers

After some 30 years of effort, high-power deuterium fluoride (DF) lasers have been developed and tested but not installed on any Navy ship as a terminal-defense weapon. The panel is not sanguine about the likelihood that DF lasers will be introduced as operational point-defense weapons during the 25- to 35-year period considered in this study. The basis for the panel's pessimism is that nose-cone technology has evolved to a point where the defeat of a modern nose cone by a DF laser will require the deposition of a greater flux of energy than can reasonably be expected to be propagated through the atmosphere in a focused beam by a laser operating near sea level at DF wavelengths.

Although DF lasers may be inherently inadequate to defeat a low-flying missile nose on, the panel does point out in the section on defense against chemical and biological attack that currently existing DF lasers are more than adequate to defeat a crossing target whose soft body is exposed to effective laser attack. Over a limited radius, DF lasers can provide an area-defense rather than a point-defense capability. Whether the value of this local area defense would justify the cost and complexity of the installation of DF lasers has not been determined.

Although some 30 years of laser programs have not resulted in an operational weapon, there is still some hope. The ideal operating wavelength for a point-defense laser would be at 1.6 μm, which is not available with any known chemical laser. However, radiation of 1.6 μm can be produced with the use of a tunable free-electron laser (FEL). All past attempts at producing a high-power tunable FEL appear to have been unsuccessful. Recently a 1.6-μm FEL has been developed that is based on the use of a RF-superconducting Linac technology.

Although this laboratory-scale laser produces an output that is at least three orders of magnitude less than the output that would be needed for a shipboard point-defense laser designed to defeat a nose-on missile at a safe encounter distance, the existing design appears to be scaleable. That is to say, there do not appear to be any first-principle reasons why it cannot be scaled to the 1- to 2-megawatt level that will be necessary. However, given the past history of high-power laser developments, it will likely be many years before all of the inherent engineering problems are solved and an operational FEL weapon will be available on Navy ships.

The prognosis for a successful FEL program is dependent on passing a number of hurdles. If the Department of the Navy funds this development at an adequate rate, and if all of the scaleup problems can be resolved without difficulty, and if the problems inherent in the operation of a shipboard-superconducting Linac can be resolved, and if adequate space and weight are available for an

installation on future combat ships, then FELs might be available as point-defense weapons some 25 to 35 years in the future.

High-power Microwave Weapons

High-power microwaves have been considered off and on for the last 25 to 30 years as a potential weapon for CMD. The concept of operation is that if enough microwave energy can be focused on an incoming missile, artillery shell, or mortar round, an electronic kill can be achieved in any one of a number of ways. For example, an HPM weapon might cause an electronic fuse mechanism to trigger prematurely and detonate the weapon at a safe distance from the ship being protected. Alternatively, an HPM weapon might burn out the semiconductor devices used for the missile's sensors, for the missile's guidance, control, and target-recognition logic, and for the missile's navigation system. Clearly, the performance of an HPM system would depend on the design of the victim missile.

HPM devices that produced multimegawatt-level outputs were reported by U.S. and Russian scientists more than 20 years ago. Indeed, it has long been possible to develop microwave power levels that exceeded the breakdown strength of air. Unlike the problem with high-power lasers, the problem in weaponizing HPM devices has not been the development of source of radiation. The problems have generally involved RF interference with own-ships electronics and the delivery of energy at a distance. Clearly, the radiation pattern of an RF antenna is very different from that of a laser. The energy that an RF antenna delivers on to a unit area of surface is inversely proportional to the square of the distance. Since the breakdown strength of air limits the amount of power that can be radiated by an individual antenna, the only way to increase the energy delivered to a distant target is to use a far-field range-focusing system. In effect the radiation from multiple antennas is focused at a single point where the target is located.

The production of an HPM weapon would appear to be a difficult but not impossible engineering problem. The problems involved are similar to the problems that might be involved in the production of an FEL weapon. Indeed, many of the source components for an FEL (electron beam source, accelerator, and wiggler field) are somewhat similar to those used in an HPM generator. HPM weapons have the added problems associated with mitigating RF interference, beam spreading, and air breakdown.

The panel's prognosis for the development of HPM weapons is about the same as its prognosis for the development of FEL weapons. A long string of issues will need to be resolved before successful weaponization. Nevertheless, the panel sees no first-principle reason why an HPM weapon could not be developed.

Ultra-Wideband Radio-frequency Impulse Signals

High-peak-power, ultra-wideband radio-frequency impulse (UWB RF impulse) signals can be used to disrupt the functioning of digital microelectronics circuits. The importance of UWB RF impulse signals as a disruption tool can be attributed to the recent development of new UWB RF impulse transmitter technologies that are small and lightweight and require relatively modest prime electrical power. The disruption potentials of UWB RF impulses have been demonstrated.

As microelectronics becomes more complex and with smaller internal signal levels, UWB RF impulse signals can disrupt the functioning of microelectronics components more effectively. Because the transmitters are very-high-peak-power systems but low-average power systems, their light weight and small size make them ideally suited for tactical applications.

System designers have long been aware that many electromagnetic sources, such as EMP impulse signals generated by nuclear weapons, high-energy cosmic rays, HPM signals, EW jamming signals, and so on, can cause significant system disruption. The emergence of new transmitter technologies that can generate UWB RF impulse signals provides a relatively new capability for circuit disruption. The panel suggests that UWB RF impulse signals should be considered as an independent approach to offensive information warfare primarily because they disrupt rather than attempt to destroy or burn out electronic circuitry.

UWB RF impulse signals are RF pulse signals of very short duration but very high peak power. The duration of the impulses may be of the order of one or two RF cycles (a nanosecond or two) and may have peak signal powers of a few hundred kilowatts to hundreds of gigawatts, depending on the antennas used to radiate them. Most UWB RF impulse transmitters can generate repetitive impulses with moderately high PRFs. Because virtually all of the computers and information systems in use today consist of digital microelectronics, the injection of UWB RF impulse signals into these systems will cause the electronic circuitry to "hiccup" or malfunction. The extent of the disruptions may only last as long as the disrupting UWB RF impulse signals are present, or in some cases, the disruptions may cause the system to require rebooting before it can again become functional. Variations in the PRF or spacing between the impulses can affect the nature of the disruptions observed significantly.

Although the disruption of the electronics hardware may be enhanced if the RF impulses have PRFs that correspond to internal periodicity, the ability of UWB RF impulse signals to enter target systems is not dependent on prior knowledge of the operating frquencies or of the bandwidth of the equipment. UWB RF impulses can enter the circuitry associated with computers, computer terminals, workstations, sensors, information networks, and communication links (and even GPS receivers) in a wide range of ways.

They may enter through the front end of RF systems (communications and sensors), through interconnecting cables between components, or through cracks and imperfect shielding in component containers. The wide bandwidth of the

impulses effectively increases the number of pathways by which energy can reach and possibly disrupt sensitive internal components.

One of the most effective transmitter technologies for producing UWB RF impulses is the bulk avalanche semiconductor switch (BASS). This technology is based on the discovery that a solid-state chip of gallium arsenide, when illuminated by a laser, will in a few picoseconds become a short circuit.

When some 10,000 to 12,000 volts are momentarily placed across a chip of gallium arsenide and the switch is placed in a simple RF circuit, the resulting avalanche of current produces about 1 megawatt of RF energy that is essentially one RF cycle in duration. A single BASS module, complete with timing circuits, is about $2 \times 2 \times 6$ inches in size and weighs less than a pound. All it needs to function is a trigger generator and a battery.

The pulse repetition frequency that can be achieved is in the order of tens of kilohertz. As a result, the average energy in the repetitive pulse train is small although the peak power is the primary parameter that affects digital microelectronics functioning. RF impulses with center frequencies from 50 to 2,000 MHz have been generated using the BASS technology.

By precision timing, many of these BASS switches can be combined to form a much higher peak power system. When configured in the form of an antenna array, peak power levels of 1 gigawatt have been obtained—and because of the gain of the array, a 100-gigawatt effective radiated power (ERP) is obtained. The individual BASS units making up the array can be timed (equivalent to phasing in a more conventional phased-array antenna) so that the beam can be steered over a 60° angular cone.

The discussion of UWB RF impulse generators may be summarized by saying that emerging new UWB RF impulse transmitter systems are low in cost and complexity, are small in size and low in weight, and require relatively low levels of prime power (average); they appear to be suitable for tactical or space applications. These technologies have resulted in the production of devices that are capable of generating extremely high peak power UWB RF impulse signals. Because of their very-high-peak signal power, UWB RF impulses have unique capabilities to penetrate and disrupt nearly all digital microelectronics hardware used in information and communication systems.

They appear to provide an important electromagnetic disruption concept that has the potential for disrupting the functioning of microelectronic digital systems. The panel believes that ways to use these new emerging UWB RF impulse signals as offensive IW weapons should be explored, and where possible, they should be converted into offensive tools.

Other Techniques

For many years attempts have been made to negate cruise missiles by means other than the hard-kill techniques discussed in the preceding sections. These alternate approaches have included electronic warfare and use of walls of water.

Electronic Warfare

The defensive approaches that are usually encompassed by the term EW include logic attacks on the weapon guidance system, the deployment of decoys or false targets, and defensive jamming of the sensors or data links of the incoming weapon.

Historically, many weapons have been fielded that had designs that made them vulnerable to logic attacks. As a result, EW systems were deployed that incorporated techniques (swept audio, range-gate pulloff, velocity-gate pulloff, and pulse on noise) that were designed to exploit logic defects of guidance designs. Unfortunately, such techniques have not remained robust for extended periods of time. Ultimately the missile designer became cognizant of the defect in their design and introduced fixes that in turn countered the EW approach that was used.

The panel believes that even though the approach of an individual technique of logic attack is unlikely to be a satisfactory solution on an indefinite basis, the approach should be followed whenever a logical vulnerability is discovered in the design of a potentially hostile class of missiles. The rapid deployment of new forms of logic attacks can keep missile designers off balance. In many cases an EW countermeasure technique may be robust long enough to cover the period of hostilities.

The guidance systems of some missiles can be defeated by the deployment of decoys and false targets. Although claims have been made that the deployment of decoys and false targets is a generic technique, experience indicates that the effectiveness of this technique may be missile specific. The problem with these techniques is that as hostile missile sensors are deployed with progressively improved resolution, the fidelity with which a decoy or a false target replicates the platform being defended will need to be increased commensurately.

The panel acknowledges that the use of decoys and false-target generation have proven to be effective techniques for CMD and believes that they should continue to be used as long as they demonstrate a reasonable degree of effectiveness against existing threat missiles. However, the panel is not optimistic that over the long term these techniques will remain effective against the expected improved resolution of future missile sensors.

The issue of using jamming to defeat the radar sensor of an incoming missile has been the subject of contentious debate over many years. A real possibility exists that in the presence of defensive jamming, the missile will automatically switch to a default home-on-jam mode of operation and defensive jamming will only serve to create a beacon to attract incoming missiles. These arguments are certainly applicable to radar sensors. It is not clear that they are fully applicable to the jamming of optical or IR sensors. Decisions relative to the jamming of non-radar-guided missiles must be made on the basis of a priori knowledge of the attributes of the missiles

that may be encountered in a given engagement. The home-on-jam problem can of course be mitigated by the use of off-platform jammers.

Although they will probably not be used in the terminal phase of attacks on naval platforms, missiles exist that are guided to the vicinity of their intended targets primarily by either or both the GPS and Global Navigation Satellite System (GLONASS). A capability to jam GPS and GLONASS signals will help to negate such missiles. The jamming of the primary U.S. navigation system, even for purposes of the defense of U.S. ships, would be a complex undertaking that would probably require new operational doctrine and special constraints on its use. Nevertheless, the panel recognizes the potential value of this jamming technique and believes that it should be explored.

Wall of Water

The objective of terminal hard-kill defense systems is to destroy an incoming low-flying missile by the application of enough energy to divert it from its track or cause it to detonate prematurely. In World War II, attempts were made to destroy low-flying incoming Kamikaze aircraft by shooting shells into the water ahead of the aircraft. The objective was to create a large jet of water that would cause the aircraft to crash. The panel has not found any records relating to the effectiveness of this tactic. Because it was not retained as a standard means of air defense, one might assume that it was of minimal effectiveness.

In a more modern version of this concept, a line charge of explosives such as that employed in the SABRE technique for clearing shallow-water mines would be fired immediately in front of an incoming missile.

In principle, such a concept could be made to work. Its development would require a substantial effort to coordinate the detection of the incoming missile with the launch of the line charge. To defend against stream raids, a substantial magazine would be required along with a means for rapidly reloading the launching device. Few data are available concerning the effect of a wall of water on a missile flying through it. Preliminary experiments have been encouraging. They have demonstrated that a water wall will stop 200-gram steel fragments. The concept is envisaged as a "last ditch" defense and could be defeated by saturation attack, as could any such system. Nevertheless, if the water wall can be maintained for a few seconds, it may be effective in handling a partial stream of low flyers. The panel believes that this concept is worthy of further exploration.

Although the panel is loath to dismiss ideas of this sort out of hand, it is not sanguine about the near-term prospects of the success of this concept. Consequently the panel would guess that if this idea were ever translated into an operational device, the transition would be unlikely to happen in the era 25 to 35 years in the future that is being considered by this study.

Defense Against Small, Fast Missile-carrying Surface Craft

Small, fast missile-carrying surface craft (such as the Boghammer) can represent a serious threat to Navy vessels operating in a littoral environment. In effect, such craft constitute rapidly moving missile launchers that are difficult to detect when they are below the radar horizon of the ship being defended or when they are lost in the clutter background of a coastal mountain range.

Conceptually two approaches may be used to negate the threat presented by such craft. The first is to defend against the missiles that it may launch, and the second is to sink the craft before it can get into position to launch its weapons.

The problem of defense against missiles launched by a high-speed surface craft is not any more difficult than the problem of defense against weapons launched by mobile missile batteries ashore. Although the difficulty of the problem varies with both missile trajectory and velocity and with the local clutter background, all of the weapon and sensor concepts discussed in the following paragraphs would be applicable for defense against missiles launched by small, fast missile-carrying surface craft.

The problem of sinking such craft prior to their launch of missiles is basically a sensor problem—not a weapon problem. A target with a relatively small RCS that is below a surface ship's radar horizon, or one that is submerged in clutter returns from the shore, represents a difficult sensor problem for an unaided surface ship. On the other hand, if an elevated platform with a well-designed sensor suite is available, the detection problem can be resolved easily.

In situations where radars are clutter limited, alternate elevated sensors may be used. IRST sensors and FLIR devices may be used. The ranges involved in these situations are relatively short and appropriate for IR.

From the standpoint of an elevated radar detector, the higher the speed of the surface craft, the easier the detection problem becomes. High-target speeds move the target out of the Doppler bins associated with the motion of surface waves on the ocean or stationary land masses. Also, high speeds tend to generate a whitewater wake that is easily detected by an elevated platform.

Once detected by an elevated sensor, almost any of the air-to-surface or surface-to-surface weapons (existing or projected) that have been discussed in this report could be used to attack and sink such craft.

Implications of Possible Future Inability to Establish a Robust Cruise Missile Defense

Albeit less than perfect, with the introduction of the CEC system, the U.S. Navy currently has a CMD system that is without peer worldwide. Some of the limitations and possible future sources of performance degradation of the CEC system are discussed above. Although the panel discusses a number of approaches to the remediation of these postulated problems, it must be recognized

that these approaches may be impractical or unaffordable to implement or may have limited effectiveness.

In the final analysis, the magnitude of the investment that the Navy will make in defensive systems will be driven by consideration of national policy and doctrine. If national policy is constrained by the tyranny of a single hit (i.e., no major U.S. combatant should be hit or sunk), then the Navy will be faced with the essentially impossible task of producing a CMD system that is 100 percent effective.

Given the general infeasibility of producing a perfect CMD, the panel postulates that the Navy will position its carriers, arsenal ships, and amphibious transports as far from the adversary's shoreline as feasible while still being able to undertake offensive operations.

For carriers this would imply distances equal to the radius of unrefueled strike aircraft plus the kinematic range of the aircraft weapons, less the distance from the target to the coast. For today's weapons and aircraft, the first two terms in this equation probably equate to about 600 to 700 miles. Twenty-five to 35 years into the future, this distance may have grown to between 700 and 1,000 miles. Although standoff distances of this magnitude (along with advances in the Navy's CMD systems) will probably serve to negate the cruise-missile threat because of the increase in aircraft flight times, they will have the effect of drastically reducing the rate of ordnance delivery by carrier aircraft.

For arsenal-type ships, the maximum standoff range will be determined either by the kinematic range of their weapons or by treaty limitations on the range of surface-ship-launched ballistic weapons. As discussed in the section "Analysis of Duration and Costs for Future Navy and Marine Corps Force-Projection Missions" in Chapter 3, the panel believes that for 21-in. rockets, this distance, in compliance with existing treaty limitations, will be 600 km. If targets for these weapons are on the average 200 km inland from the coastline, the maximum standoff distances will be about 400 km, and the existing CMD systems will again probably serve to negate the cruise-missile threat. The downside of using long standoff distances as a solution for the CMD problem is that only the largest and most expensive weapons can be used to attack the enemy. In effect, this will probably dictate the exclusive use of 21-in. weapons, which in turn implies no more than one weapon per VLS cell.

Simply put, the failure to achieve a reliable solution to the CMD problem will effectively reduce the size of the magazine of an arsenal ship and will slow the rate at which carrier aircraft can deliver ordnance on their targets.

The panel believes that if a robust solution to the CMD problem other than the use of increased standoff distances cannot be developed, then rather than accepting the twin penalties of reduced rates of fire and reduced magazine depth, the Navy will turn to other approaches to sea-based strikes and fire support for engaged forces ashore. The most obvious alternative to the negation of the

cruise-missile threat by increased standoff distance for carriers and arsenal ships would be to equip submarines to serve as shore-bombardment platforms.

Although submarine-launched TLAMs have been employed over the last 10 years, there is a general recognition that submarines as currently configured are not appropriately designed to execute the missions currently foreseen for carriers and arsenal ships. Current nuclear-powered submarines (SSNs) are configured to launch a limited number of 21-in.-diameter weapons. In that context, their magazine depth is much too small to allow them to provide a significant level of fire support for engaged forces ashore.

The panel believes that it would be possible to configure an SSN to launch 5-in. and 10-in. precision-guided missiles of the type discussed previously in the section on surface-to-surface and air-to-surface weapons. If VLS launchers were placed on a SSN and the missiles were launched by compressd air, then multiple missiles could be double or even triple stacked in each VLS cell. Under such circumstances, submarines would have a reasonable magazine depth and could become an effective source of fire support for forces ashore.

Submarines have the advantage of being relatively immune to attacks by cruise missiles. Even if a submarine needed to be on the surface to launch its weapons, it would still constitute an ephemeral target that would be difficult to target by anyone trying to attack it with cruise missiles.

Overall the panel believes that the strategy of placing long-range 21-in. weapons in VLS-equipped ships positioned at long standoff ranges and short-range weapons on large-magazine SSNs would have the effect of significantly curtailing the cruise-missile threat. In addition, this tactic could be implemented in a manner that would assure that sea-based forces had an appropriate weapon mix for both fixed and tactical targets.

Summary and Recommendations

The panel concludes that the introduction of the CEC system will result in a significant increase in the Navy's CMD capabilities. Programmed and projected improvements in weapon and sensor technology are also a reason for optimism about future CMD capabilities.

The panel is concerned that over the next 25 to 35 years potential developments may occur that might result in the fielding of all-aspect stealth missiles that, together with the limitations and constraints of possible operational situations, may result in the degraded performance of the CEC system. In such situations, the Navy could react by implementing the following:

- Improving the performance of its networked sensors,
- Improving the performance of terminal defense weapons and their associated sensors, or
- Adopting the tactics of using specially configured SSNs to launch short-

range missiles in support of engaged forces ashore and operating carriers and VLS-equipped ships with long-range weapons at the maximum feasible standoff ranges.

Given these concerns and conclusions, the panel offers the Navy the following recommendations:

- Complete its programmed introduction of the CEC system as soon as budgetary constraints permit,
- Undertake an aggressive well-funded technology effort to resolve the many complex issues that would be involved in upgrading the CEC system into a networked system of multistatic detectors,
- Undertake a review of the implications of a possible failure to be able to assure a robust and absolutely reliable CMD capability for our major surface ships,
- Support the ongoing development of EW techniques that are designed to exploit design or logic errors as they are detected in newly fielded weapon systems, and
- Continue to pursue R&D programs designed to produce effective terminal defense weapons systems.

DEFENSE AGAINST CHEMICAL AND BIOLOGICAL ATTACK

The panel was concerned about the proliferation of WMD and the ability of future Navy and Marine Corps forces to operate in a WMD environment. These concerns were also expressed by RAND studies that indicate the potential capability of enemy forces to overwhelm allied forces by WMD (particularly CBW) attacks, and by Under Secretary of the Navy Danzig, who raised the concern that U.S. forces may suffer large numbers of military and civilian casualties if WMD were used against them. The panel also recognized that chemical warfare has been used successfully in past conflicts by nations that were signatories to the Geneva Convention prohibiting the use of CW and that many Third-World nations apparently continue to develop chemical, biological, and nuclear weapons after signing treaties prohibiting them.

There is a significant difference between the measures required to defend naval forces afloat from chemical and biological weapons and those that are required to defend Marines ashore. Defense against CBW attack is more a problem in the design of defensive weapons systems. In the initial stages of a conflict, the threat of CW/BW against the fleet is from a variety of forces or delivery platforms, including TBM, cruise missiles, aircraft, fast patrol boats, artillery, and special forces. The Navy must have a layered defense against the CW/BW threat. It should contain elements of intelligence for learning where the agents are stored, what their status is, what delivery vehicles are going to be used,

and when the enemy will employ them. It is, of course, not possible to accomplish each of these tasks perfectly. For this reason, the fleet must be prepared to detect CW/BW agents rapidly and then be able to defend against them effectively. Although means of detecting CW/BW agents exist, they are not rapid, and the present wash-down approach may not be adequate to protect a ship's crew. Short of the Russian surface ship Citadel concept, there is no effective defense against these agents now on U.S. surface ships. The Citadel concept (of creating a closed, pressurized region of the essential parts of the ship) cannot be implemented on the main force of the surface fleet (i.e., the carriers), which have, for operational reasons, an essentially open construction. Navy studies have indicated, however, that the Citadel concept can be implemented on new-construction destroyer and cruiser-type ships at an incremental cost of about 10 percent of the ship's acquisition cost.

Attacks delivered by ballistic missiles against the fleet could be defeated by improved, high-acceleration SAMs. It is to be expected, however, that at some time in the future TBMs will disperse their CW/BW submunitions at high altitudes, requiring boost-phase intercepts of the attacking TBMs. This is a nearly impossible task, for the probability is low that all of the potential launch sites could be placed under surveillance and that boost-phase intercept weapons could be brought against them in a timely manner.

Defense against CW/BW of Marine Corps forces on land is even more difficult. Using masks and protective clothing in response to warning and CW/BW detection devices is the current approach. The panel is aware of developments to improve and lighten protective garments and masks and to develop detection devices and advanced medical treatments. However, short of locating and destroying all enemy storage and manufacturing and delivery means, there is no singularly effective way of defending against CW/BW. Moreover, there is the serious concern as to whether naval forces will be able to continue to effectively operate in a chemical or biological environment for more than a few hours under the best of environmental circumstances.

Since defense against CW/BW is all-important if the Navy and Marine Corps are to be able to accomplish their missions in the future, the panel recommends that the Department of the Navy implement a comprehensive review of the subject and programs to assure that this threat does not remain an Achilles' heel in the future.

6

Navy and Marine Corps Applications for Laser Weapons

ISSUES AND TRENDS

For 35 years, it has been anticipated that laser weapons will play an important role in future combat operations. Over this period, in excess of $10 billion has been spent by the three Services and DARPA in numerous programs directed toward the development of such weapons. Significant investments are continuing. It is instructive to lay out the reasons for this long delay in realization and to reassess what expectations the Navy and the Marine Corps might reasonably place on laser weapons in the future.

Numerous laboratory and field-test versions of laser weapons have been developed and demonstrated. They have worked as expected and demonstrated suitable lethality against their intended targets. The primary factors that have inhibited the transition of the technology into deployed systems are size and weight. Generally, the conceptual designs of laser weapons that are scaled for combat effectiveness are too large to be appealing to users; conversely, weapons that are sized for platform convenience generally lack convincing lethality.

There are two notable exceptions to these generalities. The boost-phase-intercept (BPI) aspect of theater missile defense (TMD) is currently a critical combat deficiency, and conventional defensive weapons cannot reach the boosters within the short engagement window (20 to 100 seconds, typically) unless they are prepositioned in the vicinity of the launch—an option not open to surface-launched weapons, and risky and expensive for weapons launched from manned aircraft. (High-altitude long-endurance unmanned air vehicles [HALE UAVs]) appear to be a rational and affordable alternative to manned aircraft for this role, but such a development has not been funded at this time.) Time of flight is not an issue with

laser weapons, since the beam transits about 100,000 times quicker than a hypersonic missile. So, despite the size and weight problems, laser-weapon developments are being funded by the Air Force and by the BMDO to address the BPI requirement. The Air Force has made a major commitment to the development and deployment of the ABL, using a chemical oxygen iodine laser (COIL), and the BMDO is continuing the development of the space-based laser (SBL) based on the hydrogen fluoride (HF) chemical laser. Neither of these are compact weapons. The ABL requires a committed Boeing 747-400 to carry it, and the SBL will be one of the largest systems ever deployed in orbit. But they are scaled to deliver lethal fluence to boosters at the long ranges that keep them out of the reach of enemy air defenses.

These exceptions point to the main reason for continuing interest in laser weapons: a superior ability to function in time-constrained scenarios. Other attributes that keep alive the interest in laser weapons are agility and low cost per engagement, as discussed below:

- *Agility.* Lasers are able to engage rapidly moving and highly maneuverable targets. It is difficult to contrive a target maneuver or speed that would seriously challenge the agility of a laser weapon. Importantly, the more agile targets are likely to be more susceptible to laser attack. If the size/weight problem can be solved, laser weapons may provide the first effective shoot-back defense of aircraft against antiaircraft missiles.
- *Low cost per engagement.* Laser weapons are expensive to buy, but inexpensive to operate. Low operating cost carries two types of advantages:
  - —Laser weapons can be freely used in training and testing, and
  - —They can be employed against proliferated inexpensive targets.

The low-cost-per-engagement aspect has prompted the U.S. Army and the Israeli Ministry of Defense (MOD) to fund development of DF chemical laser weapons for short-range air-defense applications. Significantly, targets of special interest in this development are artillery projectiles and artillery rockets—targets that are not practical for conventional guns or analog-to-digital (A/D) missiles because of the numbers to be engaged and the adverse cost exchange. The DF laser weapon will be mobile but not compact; a more compact alternative is much to be desired, and future technology may make that possible.

POTENTIAL NAVY AND MARINE CORPS ROLES FOR LASER WEAPONS

Two factors are critical in determining whether laser weapons will have a future role in the Navy and the Marine Corps:

- The feasibility of developing more compact, adequately powerful laser weapons; and
- A defensive weapons requirement that can be better met by lasers than by guns and missiles—implying threats that are soft to thermal damage and either

are highly maneuverable, are very fast, and have short exposure time, or are cheap and proliferated.

Threats that currently, and probably will in the future, fit this second requirement are as follows:

- Ballistic missiles in the boost phase (short exposure),
- Antiaircraft missiles (fast, maneuverable), and
- Artillery projectiles and rockets (cheap and proliferated).

Cruise Missile Defense

A discussion of trends and issues in CMD was presented in the section on cruise missile defense. Currently laser weapons have very low priority among Navy CMD programs. Major future efforts in CMD will concentrate on efforts to counter low observability so that weapons can engage incoming missiles farther from the ship being defended. Interest in self-defense lasers will not return until there is clear evidence of the failure of efforts to defeat stealth and there is evidence that laser fluences can be developed and delivered that are great enough to defeat the hardness of modern nose cones.

The Navy sponsored a technically successful program for the development of a self-defense laser weapon from 1968 to 1984. A much scaled-back activity continued on thereafter. Based initially on gas dynamic laser (GDL) technology, the program switched to DF lasers in 1974 because the shorter wavelength of the DF lasers (3.8 μm versus 10.6 μm for the GDL) could be employed with a smaller beam director and because the DF wavelength propagated better through the atmosphere. Program successes were marked in 1979 with the destruction of tube-launched optically wire-guided (TOW) missiles in flight and in 1989 with the destruction of a supersonic Vandal missile in flight.

The primary considerations that deflected Navy interest in carrying the program further are as follows:

- The original motivation, which was the inadequacy of guns and missiles to perform the ASMD role, diminished as guns and missiles improved;
- The laser weapon designs available were awkwardly large—the best that conceptual designs could accomplish was the size of a 5-in./54 gun mount (90 tons, 540 m^3); and
- Newer generations of ASMs became progressively harder to kill in head-on engagements, required killing at longer ranges, and demanded more performance than the DF laser, as developed, could deliver.

Theater Ballistic Missile Defense

Ballistic missiles are a threat to any concentrated forces or supplies. In particular, they are a threat to naval supply and landing ships when near shore or during

unloading operations. Defense against unitary-warhead TBMs will (presumably) be handled by ship-based systems such as the SM-2 Block IV-A air-defense missiles launched from combat vessels standing guard in the vicinity. TBMs with early-release submunitions (submunition dispersal at 60- to 80-km altitude or after booster burnout, whichever is later) cannot be addressed by SM-2 or any other terminal or midcourse defensive missiles. By the time they enter the envelopes of ground-based missile defenses, the 40 to 80 submunitions in a TBM payload will have dispersed widely and will saturate any defensive firepower. With chemical or biological payloads, these could effectively cripple military operations. Conventional submunitions would be effective against soft targets.

This is the threat at which the ABL and SBL weapon programs are directed. The ABL, assuming that it is successfully developed, would have adequate reach to protect landing forces against a submunition attack, but as it is presently conceptualized, it will probably require secure basing near the operational area. No evaluation has yet been made of ABL support for Navy/Marine landing activities, so it is not yet possible to be specific about the basing requirements. Some naval scenarios may be located too far from ABL basing options to permit them to participate—at least as they are currently envisioned—especially in fast-breaking crises.

An evaluation should be made of the utility of ABL in Navy and Marine Corps landing scenarios. The SBL does not have a basing problem, and it also could, in principle, support naval force landing operations. However, the SBL is technologically a long reach, and it is very uncertain that it will ever be carried to deployment or deployed in numbers sufficient to give continuous protection. It would be a very expensive system to deploy and to operate and would be limited in the number of available engagements. However, the SBL should also be evaluated for utility in support of naval force landing operations.

The Air Force has an interest in a compact and inexpensive alternative to the ABL, as described in the report by the Air Force Scientific Advisory Board.[1] The development of compact laser weapons, probably based on diode-pumped solid-state lasers, could lead to the deployment of BPI weapons on HALE UAVs. Such platforms would have the range and endurance to operate from remote bases and could probably support naval force landing operations anywhere in the world. However, this development, if it is undertaken at all, will not be undertaken until after funding is freed up by a successful completion of the ABL program.

Aircraft Self-Defense Weapons

Either the air-to-air missile (AAM) or the surface-to-air missile (SAM) variety has been responsible for most of the aircraft shot down in the past 40 years. Thus far, five defenses have been employed against these threats, as follows:

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[1]U.S. Air Force Scientific Advisory Board. 1996. *New World Vistas—Air and Space Power for the 21st Century, Directed Energy Volume,* U.S. Air Force, Washington, D.C., p. 65.

- Evasive maneuvering, a tactic which has diminishing utility as the threats become more maneuverable and the limitation of g-lock takes effect on the pilot before he or she blacks out.
- ECMs or infrared countermeasures (IRCMs), which are subject to the certainties of the escalating measure/countermeasure contest.
- Suppression of enemy air defenses (SEAD), in which the SAM radars and launchers are attacked.
- Stealth technology, which protects aircraft by preventing or delaying detection. There has been no capability to engage with lethal force a missile in flight. Even the new generation of agile AAMs (SA-11, Python 4, AIM-9X) are targeted at aircraft only—they lack the speed or agility to engage another air-to-air missile.
- Active protection based on a small low-cost interceptor device (SLID)-like approach. A small KKV intercept missile is launched upon warning.

Laser weapons have the capability to engage an AAM or a SAM in flight, but they must be much more compact to offer that capability as a practical option. The Air Force demonstrated capability with its Airborne Laser Laboratory (ALL) in 1984, shooting down an AIM-9C in flight. However, the laser weapon employed in that demonstration used a GDL and occupied most of a KC-135 aircraft.

The technical potential for developing a laser weapon sufficiently compact to be employed for aircraft self-defense is described in the Air Force study cited above.[2] The two key concepts exploited in the Air Force vision are energy-frugal kill and the use of a short-wavelength laser to minimize the size of the transmitting optics.

Energy-frugal kill means defeating the target with an investment of only 20 to 40 kJ of laser energy, which is less by a factor of 10 to 50 than the energy normally employed in a target engagement. The reduction of lethal energy translates into a reduction of weapon size. To accomplish this reduction, the target is engaged with a small-diameter beam (1 to 2 cm versus the more traditional 7 to 15 cm) at high irradiance (20 to 40 kW/cm^2 versus the typical 2 to 5 kW/cm^2). The high irradiance will result in a rapid, deep penetration of the beam into the sensor/guidance/control electronics of the target. At the least, this will deprive the missile of guidance, but experience indicates that the missile will likely respond with hard-over commands and possibly self-destructive maneuvers.

The small-diameter spot on target, which is the key to an energy-frugal kill, must be accomplished without employing a large-diameter beam director. This is accomplished by postulating a short-range engagement (1 to 2 km versus the typical 4 to 6 km) and a short-wavelength laser. A diode-pumped solid-state laser (DPSSL), operating at 1.06-μm wavelength, would be employed. The beam

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[2]U.S. Air Force Scientific Advisory Board. 1995. *New World Vistas—Air and Space Power for the 21st Century, Directed Energy Volume,* U.S. Air Force, Washington, D.C., pp. 15-19.

director would have a 15- to 25-cm aperture—quite compact by comparison with all previous laser-weapon developments. The ultimate size/weight goal for the weapon is 0.4 m^3/200 kg. This would permit it to be integrated into fighter aircraft. Earlier versions of the technology might take the two forms listed below:

- A compact weapon with lower power (3 to 5 kW), useful for defense against IR-guided missiles. This differs from the IRCM lasers, currently under development by the Navy and the Air Force, that must operate in-band to the IR sensor on the target and seek to damage the detector in the seeker. This is not subtle; it would be effective in or out of band and would simply burn through any IR domes and filters and destroy the sensor assembly.
- A less compact version of the ultimate weapon, suitable for defense of transport type aircraft against either IR- or radar-guided missiles.

The Air Force sees such a weapon as a technical possibility in the 20-year time frame. In higher power configurations, this technology would have applicability to both the BPI and the surface air defense roles. The Air Force is the logical Service to carry out the development of compact DPSSLs, but the Navy should encourage and participate in this effort. Although the Air Force study recommended this development highly, it has not yet been undertaken.

Projectile Defense

Surface-based air-defense weapons are needed by both the Marine Corps and the Navy. For the Marines Corps the essentially new dimension that lasers might bring to this role is the potential for engaging artillery projectiles and artillery rockets. Conventional defense weapons, guns and missiles, can in principle also engage those targets, but not in a cost-effective manner. (The Vulcan Phalanx gun has destroyed 105-mm artillery rounds in flight, but it expends many rounds per target and carries only about three engagements in its magazine.) A successful demonstration of laser-weapon capability to engage artillery rockets was recently carried out at the High Energy Laser Test Facility (HELSTF) at the White Sands Missile Range (WSMR). The target was a Soviet World War II-era Katyusha rocket, of the sort being used currently against Israeli settlements, and the lethal mechanism was warhead deflagration. Laser lethality data on artillery projectiles are not yet available, but artillery shells are inherently hard and will be difficult targets to engage with confidence.

The DF laser weapons for air defense being developed by the Army and the Israeli MOD are larger than the Marine Corps would likely want to deploy, but the Army Space and Strategic Defense Command (SSDC) is also evaluating alternative technologies, including DPSSL-based weapons, that would better fit the Marine Corps mobility requirements. The initiative in evaluating and developing surface-based air-defense weapons lies with the Army, but the Marine Corps and the Navy should support and participate with the Army in this activity

to ensure that service-specific interests are addressed. In particular, the Navy, with a long history of laser-lethality studies, should become actively engaged in the assessment of energy-frugal lethality against targets of Marine Corps and Navy interest.

CURRENT NAVY LASER PROGRAMS

The Navy's laser ASMD program, now running in low gear, has been focused on ship self-defense. As mentioned above, one of the problems with this was the increasing hardness of ASMs to frontal thermal attack—largely a consequence of the employment of much tougher radome materials—combined with increased kill-range requirements. Laser weapons are much more effective in ASMD if employed in escort defense, where the target is attacked from the side. ASMs are much softer to thermal attack from the side, and the susceptible guidance electronics and control actuators can be accessed without deep penetration. In the early 1970s, some consideration was given to laser weapons in the short-range escort-defense role, but that was dropped because the nuclear threat dictated large separations between ships in a fleet. As the Navy mission migrates toward littoral warfare and the projection of force, naval logistic vessels become high-value targets. These vessels are largely innocent of self-defense capability, and short-range escort defense may be needed when they are near hostile shores—landing operations or passage through straits. Potential threats include ASMs, artillery, and artillery rockets, all of which can be addressed by laser weapons in an escort-defense capacity. The Navy should conduct an evaluation of the potential utility of advanced-concept, compact laser weapons for the escort defense of logistics vessels.

FUTURE LASER TECHNOLOGY

Considerable resources are being invested in DF and COIL lasers, in support of the tactical high-energy laser (THEL), SBL, and ABL programs, and it is to be expected that there will be steady progress in those technologies. In addition, three other laser technologies may, over the time frame of this study, mature into weapon-scale options. These are (1) the DPSSL technology mentioned above, (2) coherent high-power diode array (CHPDA) technology, and (3) free-electron laser (FEL) technology. The DPSSL and CHPDA technologies offer compact alternatives to the DF and COIL lasers. The FEL will not be compact, but nevertheless it may offer advantages that make it attractive for some applications.

DPSSLs are the nearest-term possibility for compact laser weapons. The technology is well understood, and conceptual designs of weapon-scale systems can be generated with some confidence. The major hurdle for DPSSL weapons is the cost of laser diodes. Currently diodes cost about $30 per average watt. The optical-to-optical efficiency of DPSSLs is about 25 percent, and so the cost of

diodes is about $120 per output watt of the laser weapon. Thus, a 40-kW aircraft self-defense weapon would require nearly $5 million worth of diodes, a 250-kW weapon for ground-based air defense would require $30 million in diodes, and so on.

DARPA has a program in advanced precision laser machining that is based on DPSSLs, and one aspect of that program is diode cost reduction. The immediate goal of that program is $20 per average watt, which helps the projected costs but does not change overall costs materially. In the longer term, the DARPA program may yield a more striking cost reduction. Two factors are needed to bring the cost down below $1/watt, where it will be practical for weapons: (1) new manufacturing technology, with greatly reduced hand assembly involved; and (2) a marketplace that supports production in scale. The manufacturing technology is being addressed by both DARPA and the Department of Energy (DOE), with good prospects of significant cost reduction in the next 5 years. The DOE interest is in DPSSLs as possible drivers for laser fusion. This application requires costs in the $0.1/watt range. Success by DOE will carry along the military applications of DPSSLs, as far as cost is concerned, but laser fusion is a long-term program. A joint DOE/DOD diode cost-reduction program would be a rational national investment.

CHPDAs face the greatest technical problems, and it is not clear whether they can be made to work. If they succeed, they will have enormous impact and probably make all alternatives obsolete. The Air Force has been funding this development for better than 10 years, so far with limited success. The Air Force Scientific Advisory Board study mentioned previously, *New World Vistas,* views CHPDAs as a weapon option in the 30-year time frame (see the discussions on pp. 27 and 35 of that study).

Diode arrays are currently capable of generating a kilowatt of power per square centimeter, at 50 percent or better efficiency (low-voltage electrical input power to laser output power). These are the arrays that are employed in the DPSSLs. However, that output is developed by about 10,000 microscopic, independent lasers, and they are not coherent with respect to each other. They are suitable for pumping a solid-state laser in close proximity but would not function as a weapon. The challenge is to force those independent lasers to emit coherently.

FELs received heavy funding in the early years of the Strategic Defense Initiative (SDI) (1984 to 1988). They were envisioned then as giant, ground-based installations generating hundreds of megawatts of laser power that was to be relayed by space mirrors halfway around the world and then focused on Soviet ICBM boosters during the boost phase. As the aspirations of the SDI diminished, so also did the interest in such giant installations, and the effort was terminated. In 1985, under funding from DOE, the National Science Foundation (NSF), and the Commonwealth of Virginia, the Thomas Jefferson National Accelerator Facility initiated construction of a 4-GeV superconducting accelerator for nuclear

physics research. In 1996, under DOD funding and Navy management, an IR FEL program was spun off of this technology. The superconducting design of the accelerator cavities (1.5 GHz, with a Q of 2.5×10^9) yields a gradient of about 10 MV/m, 5 to 10 times higher than was available in the SDI program and supports more compact FEL designs. The DOD program has a series of escalating performance goals, but the ultimate aspiration is a 2-megawatt FEL, operating in the atmospheric wavelength windows at 1.06 μm or 1.6 μm, suitable for weapon applications. In addition to the use of superconducting cavities, this program will demonstrate energy recovery from the circulating electron beam and 15 to 20 percent efficiency. The application envisioned is ship self-defense against ASMs. Conceptual designs of such a weapon show it to be only slightly more compact than the DF concept, but the short wavelength will permit the longer-range engagements that are required. As a fully electric system, the FEL would be particularly compatible with future electric drive ships.

SUMMARY AND RECOMMENDATIONS

Laser weapons currently under development by the Army (THEL for battlefield air defense), Air Force (ABL for boost phase intercept), and BMDO (SBL also for boost phase intercept) may, if they are successful, provide critical combat support for Marine Corps ground warfare and for Navy/Marine Corps landing operations. These weapons address threats that presently cannot be addressed in any other way.

The panel recommends that these developments be evaluated for utility in and possible adaptation to Navy and Marine Corps scenarios.

Future developments in laser technology offer the promise of more compact (DPSSL in the nearer term, CHPDA in the longer term) or more effective (FEL, in the mid-term) weapons. DPSSL- and CHPDA-based weapons could provide the Marine Corps with a superior version of a battlefield air defense weapon, the Navy and the Marine Corps with an aircraft self-defense weapon, and the Navy with a viable escort defense ASMD weapon to protect logistics vessels during inshore operations. FEL-based weapons could provide the Navy with a robust self-defense ASMD weapon, particularly, but not narrowly, on future electric drive vessels. The Navy already has an expressed interest and active role in the FEL technology, but not in the DPSSL or CHPDA technologies, which are being evaluated by the Army and the Air Force, respectively.

The panel recommends that the Navy and the Marine Corps evaluate the impact of these compact weapon technologies on their own combat requirements and as appropriate support and participate in the Army and Air Force development.

7

Undersea Warfare Weapons

BACKGROUND

Undersea Warfare Objective

Superiority in undersea warfare is viewed as a key enabler for the Navy to execute its assigned missions of assuring freedom of the seas and control of strategic areas. Enemy submarines pose a significant threat to U.S. naval operations envisioned by "Forward . . . From the Sea."[1] The loss of life and equipment resulting from a successful enemy submarine attack on a large combatant or troop carrier could be devastating to a campaign strategy and to the national will. Thus, the major objective of the undersea warfare mission is to neutralize the undersea threat posed by enemy submarines and minisubmarines, torpedoes, mines, and unmanned undersea vehicles (UUVs). A further objective is to utilize the undersea environment for offensive action, e.g., ASW and antisurface warfare (ASUW), to attack and destroy the adversary's warfighting capability, or, as in the case of offensive mining, inhibit an enemy's freedom to operate by closing ports and sea routes to his shipping traffic. To accomplish these objectives, the Navy must maintain an inventory of technologically advanced undersea weapons and the proficiency to use them effectively. Since the operating characteristics and capabilities of the weapon typically define the engagement situation in the undersea battle space, the overall platform system effectiveness and survivability are critically linked to the proficiency of its weapons.

[1]Department of the Navy. 1994. "Forward . . . From the Sea," U.S. Government Printing Office. Washington, D.C.

Current Capability

The U.S. Navy's current inventory of weapons for undersea warfare includes three classes of weapons: (1) lightweight torpedoes, (2) heavyweight torpedoes, and (3) mines.

Lightweight Torpedoes

Lightweight torpedoes are designed as the weapon for ASW aircraft (fixed-wing—P-3 and S-3; helicopters—LAMPS, and SH-3), surface ships (Mk-32 tubes), and ASW missile payload (ASROC) and as the payload for CAPTOR mines. These torpedoes are 12 3/4 inches in diameter and 100 to 115 inches long and weigh 500 to 800 lb. The current inventory consists of two versions: Mk 46 and Mk 50. The Mk 46 was originally designed in the 1960s and, subsequently, has had various upgrade modifications, the latest version being the Mk 46 Mod 5, which improved the guidance system with integrated circuit technology of the late 1970s. The propulsion is an open-cycle engine fueled by the monopropellant OTTO-fuel II. It has a conventional bulk charge warhead. The recent introduction of the Mk-50 torpedo provides a weapon with significant performance improvement over the Mk 46 Mod 5. The Mk 50 features technology advances in (1) guidance and control (G&C)—factor-of-eight increase in search capability using multibeam, multifrequency, selectable waveforms, and accurate terminal homing implemented with digital electronics under computer control; (2) propulsion—high-power-density stored chemical energy propulsion system (SCEPS) engine that has at least twice the power/energy of the Mk-46 system and is wakeless, depth independent, and quiet; and (3) warhead—an advanced shaped-charge warhead.

Heavyweight Torpedoes

Heavyweight torpedoes are designed for submarine launch as ASW and ASUW weapons. They are 21 inches in diameter and 230 inches in length and weigh approximately 3,600 lb. The current inventory consists of two versions: (1) Mk 48 Mod 4 and (2) Mk-48 ADCAP. The Mk-48 torpedo was introduced in the 1970s as a dual-purpose ASW and ASUW weapon that had much higher speed and range capability, as well as target detection and homing advances, than the previous Mk 37. It utilizes an open-cycle engine fueled by a monopropellant OTTO-fuel II and is wire-guided. The Mod 4 version implemented improvements in speed and guidance logic. The Mk-48 ADCAP is a significant upgrade over the Mod 4, representing the modernization of the submarine-launched torpedo. It features advanced guidance through a fully digital, multibeam, multiwaveform sonar and processor with adaptive logic through on-board digital control. It has a large bulk-charge warhead capable of causing significant damage to submarines and surface ship targets.

Mines

The current inventory of undersea mines comprises CAPTOR, SLMM, and Quickstrike. CAPTOR is an "enCAPsulated TORpedo," consisting of an Mk-46 torpedo inserted into a 21-in. mine case. It is designed for deployment in deep water and its intended targets are enemy submarines. The Mk-67 submarine-launched mobile mine (SLMM) is a 19-in.-diameter submarine-launched mobile mine designed for shallow-water operation to reach waters inaccessible to other vehicles. Quickstrike is a bottom mine, intended for use in shallow water against submarines and ships.

Status

Production of the Mk-48 ADCAP torpedo was completed with delivery of the final unit made in FY 1996. The Mk 50 completes its inventory production in FY 1997. Thus, for the first time since World War II, in FY 1998 the U.S. Navy will have no ongoing production program for complete torpedoes. Further, inventory objectives for ready weapons have been considerably reduced and the older weapons are being withdrawn from service. A similar, if not more dire, situation exists for the undersea mine inventory that is approaching obsolescence, with no current plans for new acquisition. This state of affairs has been driven by significantly reduced investment in the acquisition and maintenance of undersea weapons capability, which in turn is a consequence of termination of the Cold War. Although full production has been curtailed, minimally sustaining R&D efforts are under way that could lead to improved undersea weapon performance if fully executed. These are discussed in the next section.

Ongoing Near-term Improvements

Currently, efforts are under way to upgrade the capabilities and reduce the ownership costs of the present inventory of undersea weapons. Programs are aimed at the following improvements:

- Mk-48 ADCAP G&C upgrade and torpedo propulsion upgrade,
- Lightweight hybrid torpedo,
- Torpedo commonality—commercial off-the-shelf (COTS) insertion,
- G&C software upgrades,
- Near-term R&D thrusts, and
- Analysis and simulation.

Mk-48 ADCAP Guidance and Control Upgrade and Torpedo Propulsion Upgrade

A program is under way to replace the obsolete G&C hardware (vintage early 1980s) with up-to-date electronic components to improve reliability and

maintainability and to achieve performance improvements in processing speed and memory. The hardware performance improvements provide the increased capacity needed for introducing more advanced processing algorithms and guidance software. The torpedo propulsion upgrade (TPU) is focused on reducing the radiated noise signature of the current open-cycle OTTO fuel engine system. The radiated noise reduction is intended to delay alerting the target that it is under torpedo attack. This reduces the time available for counteractions such as evasion, deploying countermeasures, and counterattack by threat torpedoes.

Lightweight Hybrid Torpedo

The lightweight hybrid torpedo (LHT) program is aimed at utilizing elements of current torpedoes, such as the Mk-50 lightweight torpedo sonar, the Mk-46 torpedo propulsion and warhead, and software of the Mk-48 ADCAP/Mk 50/6.3 G&C Program, along with state-of-the-art COTS processors to provide an upgraded lightweight torpedo (Figure 7.1). The focus of the design is an improved performance in shallow-water scenarios with a cost-effective approach achieved through use of previously designed components and available COTS hardware.

Torpedo Commonality

This thrust is motivated by the Navy's attempt to reduce ownership costs associated with undersea weapons, both for the initial acquisition of new hardware and in the life-cycle support costs for the systems. A major focus in the near term is the use of COTS electronics and processing hardware in an open architecture structure that can apply to both lightweight and heavyweight torpedoes. Such an approach has significant potential payoff as an economical means to keep weapons hardware current with the state of the art and for the reduction of maintenance support costs.

Guidance and Control Software Upgrades

Periodic upgrades of the software for the Mk-48 ADCAP and the Mk-50 torpedoes are scheduled to take advantage of hardware modifications. The process permits introduction of new functionality into the weapons in the form of processing algorithms and tactical logic in response to issues arising during developmental testing and fleet exercises. The affordability and life-cycle supportability of the complex weapon software builds are enhanced by the move toward implementation of a common set of software modules for both lightweight and heavyweight torpedoes in the future.

Near-term R&D Thrusts

In the near-term period covered by the current Program Objectives Memorandum (POM) (6 years), several R&D efforts are planned to address new capa-

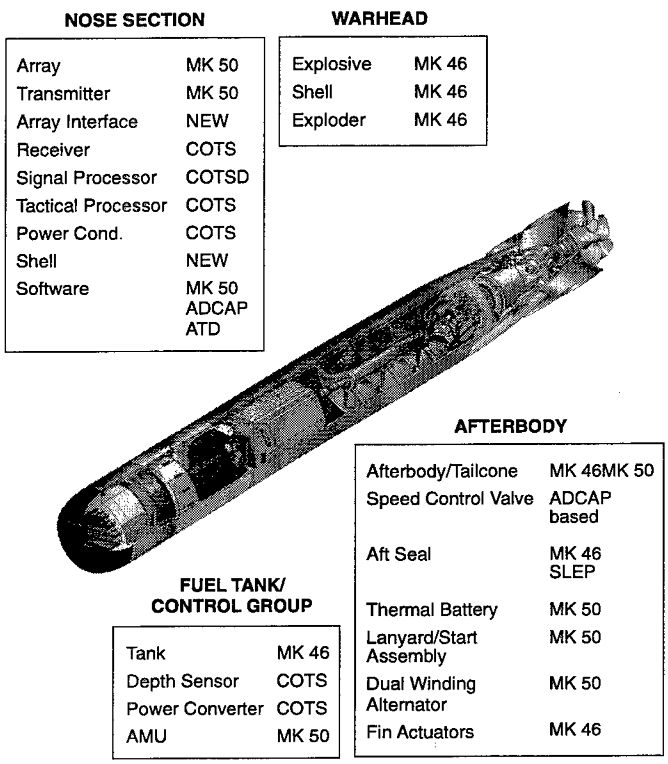

FIGURE 7.1 Lightweight hybrid torpedo configuration. SOURCE: Undersea Weapons Program Office. 1997. *Lightweight Hybrid Torpedo Configuration,* Program Executive Office for Undersea Warfare, PMS 404, Arlington, Va.

bilities in undersea weapons. These efforts are focused on the two areas of guidance/homing and propulsion. In the guidance area, the insertion of advanced processing algorithms and software is planned in order to realize performance gains in shallow-water/littoral environments and scenarios. Key issues are the detection, classification, and homing against low-signature, small submarines operating in close proximity to the boundaries. In addition to the algorithm work, an effort has begun to expand the bandwidth of operation for torpedo sonars. The wider bandwidth offers further performance-gain opportunity in adverse environments, as well as providing considerable flexibility for dealing with complex countermeasure situations. The near-term R&D in weapon propulsion addresses potential environmental and exercise support costs associated with the open-exhaust, OTTO-fueled engines. Alternatives to OTTO fuel that have characteristics of improved performance, environmental compatibility, and reduced engine turnaround costs for exercise are being considered.

Lacking sufficient resources to carry out a full development of advanced weapon ideas, an innovative acquisition process is planned during the POM time window and beyond, called the phased prototype program. The Navy plans to conduct a series of prototype demonstrations, phased over 2- to 4-year intervals, to assess performance of new designs and to judge their operational utility with fleet testing. Each prototype will be sufficiently documented and engineered to proceed to a full system development and acquisition if warranted by the operational needs at any time during the process, but this may not occur due to budgeting constraints. Succeeding prototypes will build on the lessons learned and demonstrated performance of the earlier versions.

Analysis and Simulation

The Navy continues to develop and utilize computational-based tools for analysis and simulation of weapon performance during the design and evaluation phases of R&D. This effort provides a sound engineering approach to the development of new capabilities, as well as a considerable savings in development and support costs. The specific tools being utilized are the technology requirements model (TRM)—a digital simulation for assessing conceptual designs with new technology; the general response damage code—a computational model of target structures and explosive damage effects; and the Weapons Analysis Facility (WAF)—a hybrid simulation that tests torpedo processor hardware in simulated environments.

A World War II legacy for the torpedo community has been the requirement to proof test each new torpedo being produced to certify its operability. Sample proofing of production lots is permitted when required reliability has been demonstrated. The Underwater Weapons Evaluation Facility (UWEF) is a key step toward reducing the costs associated with torpedo certification. It is a land-based facility that supports captive testing and evaluation of a fully assembled torpedo operating under its own power in a water-filled pressure vessel. This facility, shown in Figure 7.2, tests the major functions of an operational weapon within a controllable environment that replicates undersea conditions.

Assessment and Concerns

The undersea warfare weapons that exist in the Navy's operational inventory represent mature designs that originally evolved 15 to 30 years ago. Upgrades have been made and are planned to continue; however, the overall investment is viewed as minimally sustaining and far short of what is required to keep pace with evolving threats and operational needs, as well as short of what can be achieved in weapons capability by the introduction of advanced technologies and a sustained, larger effort. The payoff would be that U.S. fleet commanders could be assured of having weapon superiority in future undersea engagements.

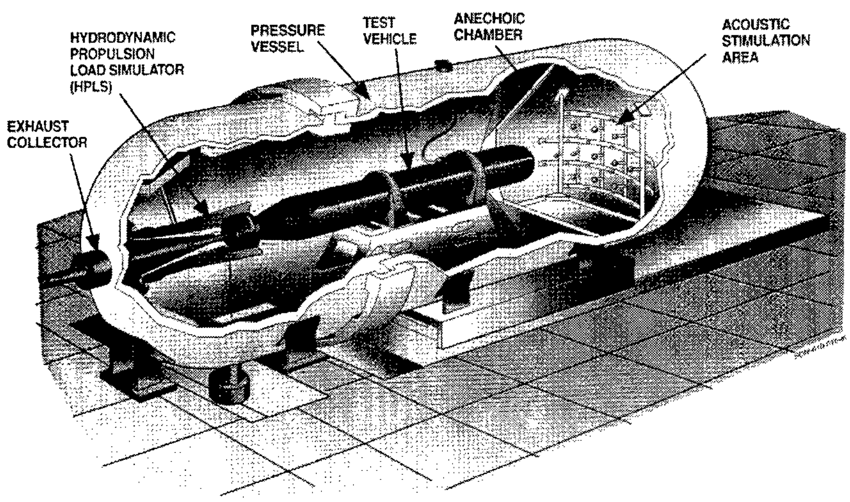

FIGURE 7.2 UWEF test system at NUWC/K. SOURCE: Test and Training Environments Department (Code 52). 1997. *NUWC Division, Keyport, Washington and the Northwest TT&E Facility,* presented to Dr. Pat Sanders, Director of Test, Systems Engineering, and Evaluation, Department of Defense, Naval Undersea Warfare Center, Keyport Division, Wash., May.

Currently, the Navy is making only modest investments in programs designed to improve the performance of existing undersea warfare weapons. This budget strategy was driven by the perception of lost acoustic advantage against the capabilities of current threats and, consequently, a focus on platform improvements. Depending on acquisition policies, the technology improvements available to the undersea weapon community clearly can be taken advantage of in a time commensurate with the rapidly changing technology. The panel and the torpedo development community share the concern that changes and improvements that are believed to be possible within the next 25 to 35 years will not be realized because of the limited attention and resources being given to undersea weapons. The projected lack of investment will delay the insertion and deployment of the improvements in performance that technology can provide.

Below is a summary of what the panel and many members of the torpedo development community believe to be principal performance and design deficiencies of current undersea weapons that should be addressed in the relatively near term (10 years):

- Effectiveness in shallow-water and complex littoral environments;
- Rapid response capability for all scenarios;
- Utilization of modern propulsion systems that are environmentally benign and provide performance gain in speed, endurance, and warhead growth;

• Radiated noise levels that alert the target during launch and runout and interfere with weapon sensors;

• Susceptibilities to advanced countermeasure devices;

• Marginal warhead capabilities of lightweight torpedoes against some projected threats; and

• Lack of an updated long-range mobile mine and a modern shallow-water-capable mine.

The next section contains a review of technologies that could be incorporated into undersea weapons to redress these deficiencies.

PROJECTED FUTURE ADVANCEMENTS OF UNDERSEA WEAPONS

In the period 25 to 35 years in the future, the current inventory of weapons will need to be replaced by future weapons with significantly advanced capabilities. The advancements required will be driven by new approaches and scenarios for engaging the target and by consideration of platform design flexibility that new weapons can provide. Although individual surface, air, and submarine ASW combatants must retain the capability to cope individually with the advancing threat, future ASW operations will likely evolve in a cooperative engagement sense that simultaneously utilizes the capabilities of multiple assets in order to effectively neutralize the threat. In such a situation, the platform delivering the weapon may not be the same as that maintaining track on the target and generating a targeting solution. Further, the possibility of weapon attacks from much longer standoff ranges are envisioned. To this end, weapons capable of long endurance and stealthy closure of the target before the attack occurs would be needed. The proliferation of sophisticated undersea weapon systems available to the rest of the world will drive a concerted effort to achieve assured self-defense against incoming torpedoes for both surface ships and submarines.

Needed capabilities and potential advancements for undersea weapons projected for the future are listed below:

• Reduced weapon size to gain platform design flexibility,

• Cooperative undersea engagement for improved deep- and shallow-water performance,

• Improved weapon stealth,

• Antitorpedo torpedo,

• Quick-reaction urgent-attack weapons,

• New weapons and tactics,

• High-performance UUVs,

• Advanced mines and mine system concepts,

• Advanced warheads, and

• Reduced acquisition and life-cycle support costs.

Reduced Weapon Size to Gain Platform Design Flexibility

Reduced weapon size will enhance platform capacity and increase mission effectiveness. Smaller weapons having equal or greater performance than current weapons will allow consideration of submarine design, weapons loadout, and launch options that could significantly affect cost and mission flexibility. Enabling technologies include high-power-density/energy-high-density propulsion, advanced guidance and control, drag reduction, noise reduction, MEMS-based safe-and-arming systems, and advanced warheads.

Cooperative Undersea Engagement for Improved Deep- and Shallow-water Performance

Improved deep- and shallow-water performance gains can come from coordinated attacks using cooperative engagement tactics and weapon/targeting integration. As applied to undersea warfare, cooperative engagement will integrate surveillance, targeting, and weapon functions to improve overall system performance. These concepts are commonplace in air warfare, but are still considered revolutionary in undersea warfare because of the lack of a technology that could provide substantial communication between weapon and platform. (Existing wire guidance systems pass only rudimentary information.) The enabling technologies that need to be matured sufficiently to contribute to new weapon capabilities include broadband sources and receivers, fiber-optic wires or acoustic modems that support high-data-rate communications, intelligent tactical control processors and algorithms, and coherent multisensor processing.

Improved Weapon Stealth

Improved quieting for weapons will delay alertment of the target until the weapon has closed range sufficiently to preclude counteraction and at the same time will reduce self-noise interference with the torpedo's own detection and tracking systems and sensors. Quieter launchers are required for our submarines to remain covert. A reduced noise signature will bring the capability to attack the target undetected from a long standoff separation range with minimized vulnerability of counterattack. Enabling technologies are reduced propulsor and hydrodynamic noise, low-noise machinery and isolation, and covert homing techniques.

Antitorpedo Torpedo

The threat to both surface ships and submarines from sophisticated undersea weapon systems available to potential adversaries motivate the need for a hard-kill antitorpedo torpedo system for achieving a robust torpedo defense. Enabling

technologies will be required to permit a small counterweapon to autonomously detect an attacking torpedo, close on it at high speed, maneuver at high rates, achieve a relatively close point of approach, and fuse a lethal warhead to kill its target.

Quick-reaction Urgent-attack Weapons

As a consequence of continued quieting by potential threat submarines, a future scenario is envisioned wherein a U.S. submarine suddenly detects the threat, perhaps at relatively close range, and is required to make an immediate response. A quick-reaction, ultra-high-speed underwater weapon (100 to 200 knots) may be required to achieve a hit on the target and to ensure ownship survival. The technology enablers for such a new weapon capability are supercavitating body hydrodynamics, high-power density propulsion, and novel guidance methods. A longer-range urgent-attack situation may arise from a cooperative engagement type of scenario wherein only short glimpses of the threat submarine are detected using data fused from several sources. This fleeting contact could require a weapon delivery capability to 10 to 20 nautical miles within minutes. The enabling technologies are rapid, airborne delivery vehicles or delivery by loitering UAVs, distributed sensor field with fused data processing (CEC), and off-board guidance and control of the attacking weapon.

New Weapons and Tactics

New weapons and tactics for future expected threats and missions include providing a submarine-launched antiair capability against patrol aircraft, a weapon for light and fast combatants, and a weapon for less-than-lethal control and neutralization. A potential solution to the submarine antiair weapon may be a variant of the extended-range fiber-optic guided missile utilized by the Army. The attack of light, fast surface combatants may be accomplished either by a small missile or a torpedo variant. Design of a weapon for less-than-lethal control or neutralization depends on developing a novel payload carried by a current undersea weapon that could immobilize the target.

High-performance Unmanned Underwater Vehicles

High-performance UUVs will potentially be deployed as remote sensors, as weapons launchers for long-range standoff attack, and for covert missions such as tagging threats. The panel believes that current technology will support the design and operation of UUVs in an increasing variety of tasks. Enabling technologies include the energy dense propulsion system for long-endurance/low-speed operation, intelligent controllers, precision navigation, advanced sensors utilizing bistatic processing, and high-data-rate communications.

Advanced Mines, Mine System Concepts

Near-term mine developments could capitalize on the advancements of torpedoes and UUV systems. A multiple warhead variant of the Mk 48 Mod 4 torpedo is envisioned as a future SLMM. A shallow-water moored mine (CAPTOR upgrade) could be developed using an LHT as a payload. In the future, minefields are envisioned as an internetted laydown of individual mines that are able to utilize the distributed sensor information they collectively obtain and are tied to an adjunct surveillance system. Enabling technologies for the next generation of mines include guidance and placement for effective warhead use, IFF capability, reliable remote control, and efficient launch-and-recover capability.

Advanced Warheads

Future advanced warhead and explosives along with highly reliable, miniaturized safe-and-arming systems are needed for the next generation of undersea weapons. Enabling technologies will be multimode warhead concepts that can defeat both submarine and surface targets in smaller packages such as half-length submarine-launched torpedoes; multistage warheads for lightweight torpedoes that can defeat large standoff, robustly constructed submarines; and explosive formulations that provide increased damage capability for a given explosive weight.

Reduced Acquisition and Life-cycle Support Costs

Reduced acquisition and life-cycle support costs will be achieved through greater commonality of hardware, software, and processes for a variety of applications. Common torpedo technology will be one of the primary goals in all future undersea weapon development. The common undersea technology vision seeks to replace the variety of current configurations with generic vehicles, all of which would use a common propulsion and energy technology and common guidance and control and common sensor technology, with payloads tailored to the mission (i.e., torpedo, antitorpedo, or mobile mine). Employing this philosophy will yield significant savings in software requirements, development, coding, testing, and life-cycle maintenance, as well as commonality of parts, manuals, and training. Simulation-based design will be incorporated in sonar and torpedo development as a central thrust toward efficient, coherent, and concurrent design processes that produce technical advances rapidly and at markedly reduced cost.

ENABLING TECHNOLOGY OPPORTUNITIES

The following sections provide a detailed discussion of the enabling technologies that have been referred to above as being necessary for the advancement of undersea weaponry.

Guidance and Control

The undersea weapons guidance and control technology effort is directed toward the detection, classification, and homing on low-target signature, low-Doppler (speed) submarines operating in complex, littoral, and shallow-water environments. Such environments present considerable challenges to an autonomous homing torpedo in the forms of increased reverberation and background noise, severe multipath acoustic propagation, high density of false targets, and considerable environmental variability. The situation becomes more highly complicated with the introduction of sophisticated torpedo countermeasures into the scenario. The enabling technologies required to address the above issues include the following:

- New signal waveforms that permit simultaneous low-/high-Doppler search.
- Multiprocess detection algorithms with output data fusion to achieve robust performance under varying conditions.
- Advanced classification approaches based on hierarchical clue sets and fuzzy logic decision structures.
- Adaptation of processing and weapons tactics based on in situ measurements.
- Intelligent tactical control architectures that optimize attack based on perceived uncertainties and react adaptively to unforeseen circumstances.

Emphasis in the future will be on achieving a considerable expansion (factor of 20 increase) in operating bandwidth of undersea weapons. The enabling technologies are hybrid piezoelectric-magnetostrictive acoustic transducer designs that provide high-efficiency broadband transmit-and-receive capabilities. Correspondingly, advances in signal processing will be made based on frequency-agile sonar designs, high-bandwidth coherent processing, wideband wavelet theory implementations, and high-resolution imaging. The increased sonar bandwidth and processing are required for dealing with advanced countermeasure scenarios in shallow-water environments.

Guidance and control for weapon concepts of the future will focus on integration of data and information from off-board sources in a cooperative engagement sense. The technology will include wideband, coherent intersensor processing. A new concept termed bidynamic processing has been formulated that requires relative motion between two spatially separated sensors to achieve high resolution, localization of sources, and target echoes. Long-range UUV-like attack weapons will require the capability to process target signals in a bistatic operating mode and be capable of wideband data communication to undersea surveillance sensors.

Energy and Propulsion Systems

Torpedo Systems

Given the fixed dimensions of a torpedo, the amount of its internal volume that is allocated to internal storage of fuel and oxidizer and the energy conversion

process is limited. As a result, there is a continuing requirement for improved performance of the energy systems that are used. Although the improvement that is sought is generally focused on performance gain through increased power and energy system densities, other objectives such as affordability, reliability, safety, stealth, robustness, and environmental compliance are also important.

Current torpedo energy storage systems can deliver about 45 W/h/kg. As a result of ongoing R&D programs, the panel anticipates that, as shown in Figure 7.3, future torpedo systems may store and deliver about 180 W/h/kg. Future torpedo designers may use this postulated increase in available energy to increase torpedo range (for the same speed) by a factor of four; or alternatively for the same range, body shape, and propulsion efficiency, they may achieve a doubling of speed. Propulsion technology is one of the major building blocks of undersea weapons. The broad technical objective of propulsion efforts is the provision of safe, environmentally friendly power sources having the highest possible energy and power densities and the lowest possible life-cycle costs. The specific technical objectives for propulsion research includes the JP-5-based near-term replacement for OTTO-fuel II that reduces turnaround costs and hazardous waste while improving performance and supports multiple exercise runs per engine. This will require the development of the following:

- Compact, quiet, high-performance turbines and other thermal engines;
- Compact hydrocarbon combustors;
- Reactive thermal storage materials;
- Aluminum, seawater-based vortex combustors and hybrid rockets supporting quick-reaction weapons;
- High-energy density hydrox for half-length torpedo;
- Adaptive noise control;
- Liquid metal thermal engine technology;
- Closed or semi-closed operating-cycle engine alternatives;
- Liquid metal fuel reactions;
- Advanced drag reduction techniques; and
- Compact hydrogen and oxygen storage and production systems.

The technical objectives for current torpedo propulsion development efforts flow directly from the torpedo propulsion road map as shown in Figure 7.4. Although this road map addresses submarine-launched torpedoes, the panel anticipates that the same technologies will be used for multiplatform weapons. Commonality is a major torpedo goal. Smaller diameter versions of all these powerplants can be developed.

Unmanned Underwater Vehicles

The broad technical objective of current UUV energy system research and development programs is to augment advanced heat engines with thermoelectric,

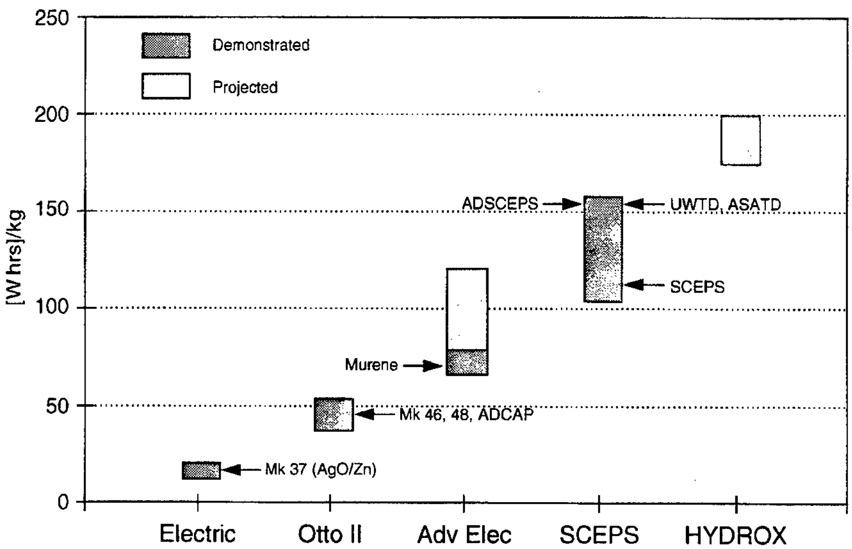

FIGURE 7.3 Torpedo energy densities. SOURCE: Hughes, Thomas G. 1996. "Weapons Thermal Propulsion," Applied Research Laboratory, Pennsylvania State University, presentation to the Panel on Weapons, October 17.

thermionic, and thermal photovoltaic converters to produce hybrid energy systems with higher energy densities than are currently achievable by nonnuclear means. Implicit in the effort is the continued development of combustion/reaction processes for new reactant couples and the continued development of new, compact, high-performance energy-conversion systems. These areas are shown as follows:

- Flywheel and thermal energy storage systems,
- Thermoelectric and thermionic generators,
- Powder metallurgy wick combustors with integral heat exchangers and product separators,
- Environmentally sustainable energy systems,
- Integrated motor/propulsor,
- Micro-flow-control techniques,
- Rechargeable batteries for targets and UUVs,
- Hybrid electric/thermal power systems, and
- Fuel cells.

The panel believes that improvements realized as a result of these efforts will be supplemented by ongoing advances that are foreseen in the technology of Stirling engines, microturbine/generators, heat pipes, and battery technology.

The principal Navy program for UUVs in early years covered by this study is

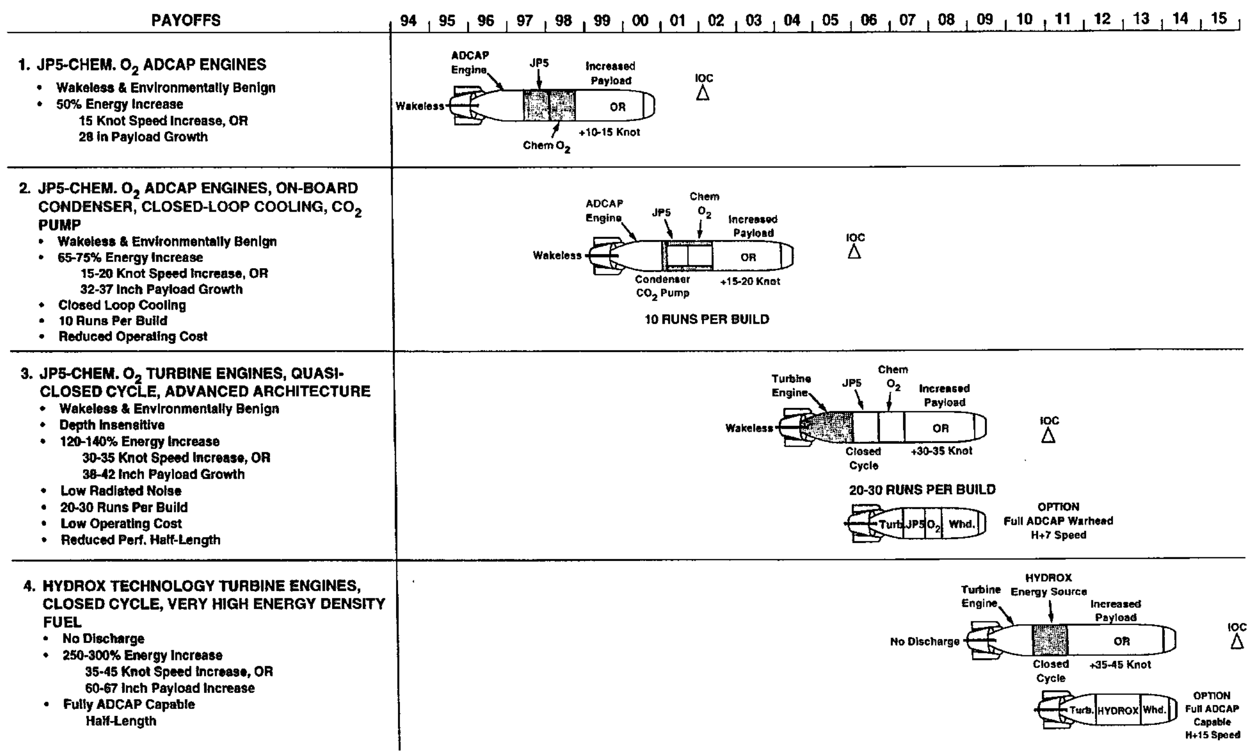

FIGURE 7.4 Heavyweight torpedo propulsion evolution. SOURCE: Hughes, Thomas G. 1996. "Weapons Thermal Propulsion," Applied Research Laboratory, Pennsylvania State University, presentation to the Panel on Weapons, October 17.

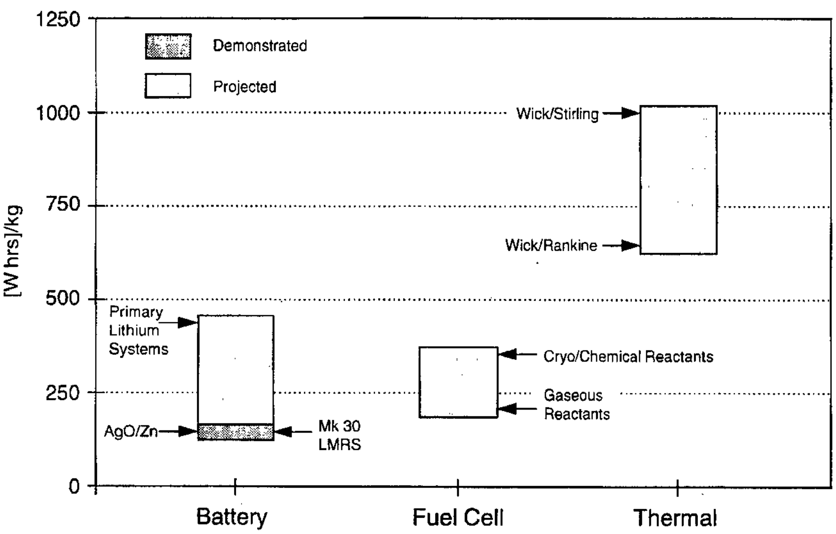

FIGURE 7.5 UUV energy densities. SOURCE: Hughes, Thomas G. 1996. "Weapons Thermal Propulsion," Applied Research Laboratory, Pennsylvania State University, presentation to the Panel on Weapons, October 17.

the Long-range Mine Reconnaissance System (LMRS). This application will require the change-out of energy sections of the UUV on submarines, requiring the resolution of the technical issues involved in ship handling, storage, and recycling of UUV components. Potential energy systems for UUVs are shown in Figure 7.5. The panel believes that the Wick-Rankine and Wick-Stirling systems represent potential breakthrough technologies for UUV applications.

Warheads and Explosives

The long-term goal of warhead technology is to develop a lightweight warhead that will guarantee hull rupture against the entire submarine order of battle. For double-hull submarines, the warhead is detonated against the outer hull, making rupture of the pressure hull difficult. Technology is being pursued for a lightweight multimode warhead that combines a shaped-charge section with an improved bulk charge explosive. Reactive materials in the form of compressed powders and/or solids are being investigated to enhance damage to submarine double hulls from shaped-charge jets or explosively formed projectiles (EFPs). Because of the limitation of a small warhead, the hole size using conventional shaped-charge liners in the multimode warhead will be relatively small. By placing a reactive material at the base of the liner basal insert, the tail of the jet will contain reactive material that will increase the hole size in the pressure hull

significantly. Also being investigated are reactive materials such as titanium diboride that can be thermally or shock initiated to generate a tremendous amount of heat. The reactive material can be placed in the nose of the torpedo behind the sonar array frame so that the torpedo literally burns its way through the outer pressure hull upon impact. The ability to burn through a 0.5-in. steel plate within 90 ms has been demonstrated. The technology goal is to increase the heat flux from 10^4 W/cm^2 to 10^6 W/cm^2, which will enable burnthrough within 1 to 10 ms.

To achieve hull rupture of the hardest double-hull submarine, the ability to burn through the outer hull must be combined with the development of a new generation of explosives. The goal is to increase the explosive energy transmitted to the target by a factor of three compared with that of our best state-of-the-art explosive, namely, PBXN-103. This will require a technology breakthrough in new explosive ingredients. Novel fuels and oxidizers are being developed to increase the overall caloric content of the explosive and to control the rate of energy release. The net result will be more efficient use of energy available in the warhead as well as the ability to tailor the detonation process to optimize target coupling effects. Table 7.1 summarizes the evolution of technology to achieve this. The first column of this table lists generic target hardness. A target in category A would be a single-hull submarine that has not been strengthened for deep immersion. A target in category B would be a single-hull submarine that is made of high-strength steel and has been reinforced for deep dives. A target in category C would be a double-hull submarine with modest standoff distances between hulls. A target in category D would be a large, highly compartmented submarine with multimeter standoff distances between the hulls.

A major focus in undersea fuzing is incorporation of MEMS, developed for other industrial applications, as an enabling technology for small, low-cost weapons. MEMS-based safe-and-arming systems are being developed that will be an order of magnitude smaller than current devices as well as being less costly and more readily available because of an expanding industrial base for MEMS. Additionally, current technology programs have demonstrated the feasibility of using active electromagnetic (EM) fuzing systems which have demonstrated a 90 percent reduction in required power for a given range. EM fuzing may be required in environments that are acoustically messy, such as shallow water or ship/submarine wakes.

Analysis and Testing Technology

Simulation-based Design

The future development of weapons will be accomplished utilizing a simulation-based acquisition approach. A virtual, three-dimensional model of the design will be captured in a computer database and evolved as the design is changed. The virtual model will be tested in various scenarios with computer-simulated environments and targets. The design will be iterated based on performance effectiveness and detailed cost models for development, production, and life-cycle support.

TABLE 7.1 Evolution of Warhead Technology to Achieve Hull Rupture

		Warhead		
Threat Increasing Hardness	Baseline Mk 46 Mk 103	Multimode 25 percent SOA and SC	Hybrid Mk 46 Three times SOA	Burnthrough Three Times + Reactive Material
A	Rupture	Rupture	Rupture	Rupture
B	Marginal rupture	Rupture	Rupture	Rupture
C	—	3/4-in. hole 2-in. reactive	Rupture	Rupture
D	—	—	—	Rupture
(Normalized) Torpedo lethal range	1.0	1.1	1.7	1.7

SOURCE: Jack E. Goeller, Advanced Technology Research Corporation, Burtonsville, Md., and Edward Johnson, Naval Surface Warfare Center, Indian Head Division, Indian Head, Md., 1996.

A future goal is to achieve semiautonomous design optimization for certain of the weapon subsystems based on validated cost/performance design databases.

Weapon Test Simulators

Torpedo testing by dry land simulation offers many benefits now, and the impact of technology should greatly enhance this capability. However, it can never completely replace full-up testing. The panel believes that the dry land testing by simulation approach to torpedo certification is sensible so long as a continuous effort to verify and validate the predicted performance is maintained.

Explosive Detonation Physics

The capabilities of improved modeling of detonation processes coupled with improved material failure models will be required in end-to-end modeling for warhead design and evaluation and to reduce live fire testing. The projected increase in computer power in the future will significantly improve the Navy's ability to model underwater explosion effects for complex targets, to predict the response of buried anti-invasion mines, and to accurately predict three-dimensional shock and bubble effects at a fraction of present computing times. Improved modeling of detonation physics will be the basis for laboratory-scale tests of warhead explosives which would reduce the need to perform repeated large-scale testing each time the explosive formulation is modified during warhead development. The panel notes that extensive live fire testing will be prohibitively expensive in the 21st century and consequently less likely to occur. Accurate and dependable computer simulations

will provide the warhead and ship designer with the tools needed to design structures without resorting to testing every interaction, thus resulting in a 50-percent reduction in warhead development costs.

Torpedo Defense Technology

Torpedo defense, as used in this section, refers to the use of a torpedo to find and kill an attacking torpedo. Torpedo defense technology encompasses all of the major technology areas involved with undersea weapons applied to an antitorpedo torpedo (ATT) mission. These efforts include guidance and control, propulsion, propulsor, vehicle systems, environmental acoustics, and modeling and simulation technologies.

The panel believes that currently existing technology would support the development of an operational capability to defend ships and submarines against torpedo attacks by using another torpedo to find and kill the threat torpedo. Because it would be a first-time-ever capability, the near- and mid-term technical objectives of any ATT program would be to demonstrate the feasibility of the concept. Based on its review of existing capabilities, the panel believes that an ATT capability can be demonstrated using an existing 6.25-in. vehicle. A successful demonstration of an ATT would establish the hardkill torpedo defense concept. The panel found that although the concept of hardkill torpedo defense capability is heartily supported at all levels of the Navy, a "show me" approach to its procurement exists. Because of past technical difficulties in counterweapon development, there is a clear position of keeping hardkill torpedo defense in the technology development phase until the capability can be convincingly demonstrated.

Mines

Visionary tactics for distributed interactive minefields of the future rely on the ability to communicate reliably between mines and sensors, to perform autonomous reconnaissance, and to contain sufficient intelligence to perform selective targeting. Enabling technologies for these advances are expected to be common technologies shared with the torpedo and UUV developers.

SUMMARY AND RECOMMENDATIONS

Impact of Undersea Science and Technology on Navy Capabilities

Guidance and Control

Concepts for guidance and control of the future will be enabled by technology to provide the following:

- Communication, networking, and interoperability among weapons and platforms of all classes;
- Intelligent control, selective targeting, and IFF for all weapons; and
- Performance against quiet targets and discrimination against countermeasures in acoustically challenging environments using wide-bandwidth signals.

Energy and Propulsion Systems

Energy systems of the future will strive to produce higher energy densities than are currently achievable. These achievements will have the following results:

- Environmentally sustainable long-endurance energy systems, and
- Multimission UUV capability.

Propulsion technology growth will be a major influence on the future direction of undersea weapon capabilities, as it is one of the major building blocks of an undersea weapon. This growth will result in the following:

- The emergence of safe, environmentally friendly power sources having the higher energy and power densities and the lower life-cycle costs; and
- Weapons with compact, quiet, high-performance turbines and other thermal engines.

Warhead Research

Warhead science and technology developments are expected to have a major impact on the Navy weaponry capabilities in the 2035 time frame. These are summarized as follows:

- Small cost-effective undersea weapons of all types, capitalizing on MEMS fuse technology and more energetic explosives;
- Improved weapon system safety by insensitive munition compliance;
- Robust lightweight torpedo warheads (12-in. diameter) capable of rupturing the hull of the projected robustly constructed submarine threat;
- Half-length heavyweight torpedoes with small explosive warheads capable of rupturing the hull of the projected submarine threat while significantly increasing the loadout of torpedoes on U.S. submarines;
- Small, effective sea mines with significantly increased lethal radius against surface ships and submarines, and reduced delivery requirements compared with those of the current Quickstrike mines; and
- Reduced weight and weight of explosive systems to counter enemy sea mines, surf zone, and beach mines.

Analysis and Simulation

Computing power has increased to the point that detailed simulation-based design and testing have become an integral part of S&T development. This trend is expected to increase to the point that simulation tools will be indispensable to all phases of weapon design and testing. Some of the major impacts are listed below:

- On-land encapsulated test facilities for torpedo evaluation and certification providing large cost savings and better test conditions than live firing;
- Simulation-based design used as an efficient, cost-effective tool for all phases of torpedo design and performance evaluation;
- Modeling and simulation providing warhead designers with the tools to design and evaluate new warhead approaches against a wide spectrum of targets without extensive testing; and
- Torpedo vulnerability as assessed by physics-based models for lethality studies supporting the design of counterweapons.

Torpedo Defense Technology

The development of a torpedo counterweapon will rely on commonality of technology with the other thrusts listed above. Its impact will be seen on the torpedo-defense hard-kill capability to enhance naval defensive tactics by providing point defense against hostile torpedo attacks from submarines.

Recommended Navy Actions

The panel recommends that the following enabling technologies be pursued to provide a focus for future investment in the technologies that the panel believes show the highest promise to have broad applicability and high-leveraging potential among current and future weapons concepts. These technology areas will enable the development of next-generation concepts and tactics for new classes of weapons including half-length submarine-launched torpedoes having capability equivalent to that of current weapons, antitorpedo torpedoes for protection of submarines and surface ships, unmanned long-endurance UUV-like weapons, rapid-attack weapons, and networked intelligent mine fields.

The panel believes that the Navy must commit to a sustained investment in S&T and R&D for undersea weapons to maintain the technological edge needed for undersea superiority. Those high-leverage technologies that provide insertion opportunities into current systems should be pursued now to achieve needed performance improvements and cost savings, specifically:

- Broadband sensor and signal-processing technology that provides increased capability in difficult littoral environments and aggressive countermeasure scenarios.

- Propulsion alternatives to OTTO-fuel that provide performance gain and reduced life-cycle support costs.
- Simulation and modeling that incorporates accurate computational models that characterize the environment and target response that can lead to a reduced dependence on in-water weapon tests and live-fire warhead tests.
- High-energy density technology for low-power autonomous weapons and long-endurance UUV applications:
  - —Liquid metal wick combustion;
  - —High-efficiency, integral Stirling cycle electric generator; and
  - —Hybrid thermal/electric energy system.
- Cooperative engagement capabilities involving:
  - —Broadband, multiple sensors; high-data-rate communications; intelligent information system network architecture; and
  - —Coherent intersensor processing, bidynamic localization, higher-order spectral imaging, and fuzzy logic adaptive decision structures.
- High-power-density propulsion technology for high-speed weapons and smaller torpedoes with equivalent or better capability:
  - —Aluminum-seawater vortex combustion;
  - —HYDROX, chemical H_2O_2 storage and reaction in high-temperature thermal engines; and
  - —Supercavitation hydrodynamics.
- More energetic explosives and increased warhead performance exploiting new materials and novel damage mechanisms:
  - —Combination of reactive materials and enhanced explosive effects,
  - —MEMS safe-and-arming designs, and
  - —Multiple-mode warhead design concepts to tailor warhead to preferred damage mechanisms.
- Simulation-based design that incorporates virtual prototypes and physics-based performance evaluation models for reducing costs in acquisition and testing and evaluation for new weapon concepts.
- Torpedo defense concepts based on quick reaction or intercept weapons designed to attack torpedoes.

8

Special-purpose Devices and Techniques

BACKGROUND

Traditionally, naval weapons have been considered to be ordnance devices that permitted the explosive release of chemical or nuclear energy to destroy enemy targets or personnel as a result of the effects of local overpressure, conflagration, or high-velocity fragments. Through the years, a realization has developed that there are limitations in the ability to cause a determined adversary to cease organized resistance solely by the delivery of ordnance devices. Also, inaccurate weapon delivery in urban areas has caused much unintended damage to people and structures that were not the intended target for the weapon. Such collateral damage frequently served to increase the resolve of the hostile population to continue the conflict.

In the past, other approaches have been tried with limited success. Naval blockades have been used to disrupt an enemy's commerce and access to critical raw materials necessary for the continuation of conflict. Ultimately such approaches have tended to weaken an enemy's ability to continue a conflict but have not in themselves been the dominant cause of conflict termination.

In recent years, new technologies have begun to emerge that can be used to limit an adversary's ability to carry on organized resistance and to discourage the local population from continuing to support the conflict. The panel believes that there is reason to expect that the special-purpose weapons and techniques discussed in this chapter may become one of the more important means used by naval forces to achieve conflict termination in some situations.

INCAPACITATING (LESS-THAN-LETHAL) WEAPONS

Background

In many operations, particularly those involving operations other than war (OOTW), it will be essential that naval forces have incapacitating (less-than-lethal) weapons available so that lethal weapons do not need to be used. Such situations might occur, for example, when large hostile crowds of unarmed people attempt to attack and overrun a numerically small group of Marine Corps personnel. Although a squad or platoon of marines is perfectly capable of protecting itself from unarmed crowds using the weapons with which it is equipped, it is undesirable for U.S. armed forces to take actions that result in the killing or wounding of unarmed civilians.

The panel believes that the imperatives of OOTW and combat operations will result in the extensive development and deployment of incapacitating weapons and devices that have a capability to immobilize land vehicles, ships, and aircraft in addition to human beings.

Other applications for incapacitating weapons involve hostage recovery situations. When terrorists take hostages, there are three approaches that the United States can employ, as follows:

- Negotiate with the terrorists and accede to some or all of their demands,
- Overwhelm them with a superior military force but risk the death of some or all of the hostages, or
- Use incapacitating agents to render the terrorists incapable of effective resistance.

If the capabilities to execute the third approach were reliable, it would generally be the approach of choice. The panel believes that incapacitating weapons, agents, or techniques constitute a sufficiently attractive approach for the management of such situations so that a significant effort should be undertaken to develop and produce them.

Sea- and Air-control Devices and Weapons

The panel is also confident that the next 25 to 35 years will witness the development of weapons and techniques that allow the immobilization of ships and that have the ability to force aircraft to land without shooting them down. In times of conflict, for example, it will be important to interdict the flow of oil to or from an adversary, but the sinking of large tankers is an unattractive approach because it would cause an ecological disaster. The panel is convinced that a multiplicity of devices and techniques can and will be developed to immobilize ships without sinking them. These might include small torpedolike weapons that home on and destroy the screws of a surface ship, but otherwise do no damage. If

permitted by applicable treaties, alternative approaches might involve the use of laser dazzlers to incapacitate personnel on a ship's bridge or the fast rope delivery of SEALs onto the deck of a ship being interdicted. Whatever techniques are ultimately developed, the naval forces of the future should have one or more capabilities to immobilize hostile ships.

In times of conflict, a need exists to inhibit air traffic. Military aircraft are, of course, valid targets for air-to-air weapons and do not constitute a problem beyond those discussed in Chapter 4 of this report. Currently, however, the problem of forcing nonmilitary aircraft to land without shooting them down does not have a solution. Although in times of conflict civil aircraft are unlikely to fly in a combat zone, history has provided many examples of their being captured by terrorists or used to transport terrorists to a sanctuary or to transport restricted material (e.g., drugs).

Solutions postulated for the problem of forcing a nonmilitary aircraft to land are typically complex and scenario dependent, and the technical approaches are speculative and risky. They include the following:

- The placement of additives into the fuel, to cause engine failure;
- The use of high-power microwave (HPM) pulses to destroy electronic components used to control the aircraft;
- The sending of false navigational signals and ground-controller instructions that cause aircraft to land at airports other than the one intended; and
- The use of lasers to blind or dazzle the cockpit crews.

Although the concepts proposed are not on firm technical or operational ground, the panel is inclined to believe that the importance of a capability to force an aircraft to land should result in an effort to develop it.

Personnel Incapacitation Techniques

Many techniques exist or have been suggested for incapacitating, channeling, or controlling large numbers of hostile people. The most primitive of these techniques involves the use of concrete barriers or rolls of concertina wire. High-pressure water cannons and rubber bullets, as well as tear gas, have also been used for such purposes. Newer approaches involve the deployment of impenetrable barriers of sticky foams or slippery films that are difficult or impossible to walk on. More speculative approaches call for the use of infrasonic generators that induce nausea or lasers that are used to blind or dazzle hostile crowds.

In recent years, the military value and the potential political liabilities associated with the use of both the newer and the more speculative approaches mentioned above have been a subject of much debate. Acknowledging the unresolved problems associated with the use of incapacitating antipersonnel weapons, the panel remains convinced that such weapons will be developed and refined and will prove to be an essential component of the

weapons available to support naval forces in situations where the use of classic lethal weapons is inappropriate.

The primary use of these techniques will occur when U.S. forces are involved in OOTW in the presence of a hostile population. Present systems for response to hostile crowds are marginally effective and acceptable. New approaches that are simple to employ and more effective than current techniques are needed. The panel is persuaded that given the significant recent and probable future employment of naval forces in OOTW, in the presence of hostile civil populations, the priority for the development of incapacitating weapons and techniques should be high.

Antiterrorist Weapons

Antiterrorism is a complex subject that has been the subject of many years of study, trial and error, and outright failure. Control of terrorism is generally regarded as a problem for the intelligence and law enforcement communities. The perception is that if a terrorist group can be infiltrated and its communications exploited, then there will be some hope of negating its activities. Unfortunately, this approach to combating terrorism frequently fails, and a classic hostage crisis or random destructive act occurs.

Navy SEAL teams and some Marine Corps units are trained to respond to such situations with conventional weapons. Although such units have formidable firepower and will ultimately prevail in a hostage recovery operation, there is a significant risk of losing hostages when SWAT team tactics are used.

The panel believes that if a hostage situation cannot be resolved by negotiation, the use of incapacitating techniques is the preferred approach. Required are techniques that will immobilize both terrorists and hostages in the structure held by the terrorists. Rapidly generated, large immobilizing foams or gaseous agents that induce a deep sleep would be attractive agents for these purposes. The panel believes that weapons or capabilities of this sort constitute a valuable capability for naval forces engaged in hostage recovery actions and warrant an effort toward development.

Summary

All evidence available to the panel indicates that during the next 25 to 35 years incapacitating (less-than-lethal) weapons and techniques will play an increasingly important role. Although their importance in a conflict with a major peer competitor or in a major regional contingency might be restricted, their importance in OOTW or in hostage standoff situations will be significant.

From the standpoint of weapon maturity and operational concepts for their use, the techniques discussed in this section are in their infancy. The panel believes that naval forces should do the following:

- Concentrate on the development of tactics and doctrine for the use of incapacitating weapons;
- Develop tactics and techniques for forcing aircraft to land and ships to divert as directed by U.S. forces; and
- Continue the development of incapacitating weapons that are more effective, reliable, and politically acceptable than current devices.

As an added cautionary note, the Department of the Navy must recognize that public release of the specific technologies to be employed will allow countermeasures against U.S. forces or interests.

TECHNIQUES FOR OFFENSIVE INFORMATION WARFARE

Background

Although the terminology "offensive information warfare" (IW) is of relatively recent usage, the activities encompassed by this term have been practiced by military forces throughout history. Broadly stated, the objectives of offensive IW are to deny, deceive, disrupt, destroy, and/or exploit (D^4E) an adversary's information systems. The implications of each of these five approaches to IW are considered below.

The Navy is only one of several entities performing activities in the area of offensive IW. In any given situation, a theater CINC determines what offensive IW actions are undertaken along with specific target identification, times and extent of attacks, and rules of engagement (ROEs).

The specific techniques used for purposes of D^4E are generally classified. More importantly, as the technologies for storing, processing, transmitting, and displaying data and information change, so must the techniques for D^4E. Given the extraordinarily rapid rate of change in information technology, it must be expected that the techniques used for offensive IW must also change rapidly. Techniques that may have been used successfully as recently as 1 or 2 years ago may not be effective against current information systems. Thus, the panel believes that there is little to be gained from speculations concerning the specific IW techniques that are in current usage or that might be in use 25 to 35 years in the future. Rather, the panel attempted to consider general classes of targets and objectives for IW and assumed that the necessary techniques to achieve these objectives and attack these classes of targets will be pursued for operations against future technology.

Since this study is about future naval forces, it is reasonable to ask why the Navy and Marine Corps should be concerned with IW, since IW is under the control of the theater commander who selects the IW targets and authorizes the use of specific IW techniques. Although the answer is rather complex, the response boils down to the fact that the implementation of many IW techniques

can only be accomplished or can best be accomplished from and by naval platforms. Under certain circumstances, the best place to locate offensive IW tools that have been developed by another Service or agency might be aboard a naval vessel. Service or agency ownership would be somewhat irrelevant. As an example, for a given mission an Air Force crew might be stationed on a naval vessel to operate and maintain specific equipment. A naval officer would be in command of the ship but would place the ship in locations requested by the Air Force IW team leader so that a CINC-designated mission could be accomplished.

Even when the United States has base rights in a country contiguous to an adversary, the use of IW techniques may be infeasible or undesirable. A host country might elect to prohibit certain IW actions or demand access to closely held IW capabilities in return for granting permission for the use of IW techniques from its territory. Since U.S. Navy platforms are in effect sovereign U.S. territory, there are no external constraints to IW operations from naval platforms. The panel also recognizes that in a world with global information networks, access can often be achieved from any location in the world. Certainly if IW techniques can be executed from within U.S. territory, it is preferable to do so using shore-based rather than sea-based systems. Unfortunately, many IW techniques can only be executed from forward-deployed platforms.

Information Warfare—Denial (of Service) Techniques

The military objective of denial-of-service attacks is to deny an adversary information, situational awareness, and the ability to communicate, thus precluding the exercise of the functions of command and control of combat elements.

A very simple example of a technique that results in denial of service would be the use of a computer-driven telephone dialing device (Demon Dialer). If one wishes to deny telephone service to a particular extension, one simply sets the Demon Dialer to call the number repetitively. The party at the extension being attacked can either leave the phone off the hook, thereby denying him- or herself use of telephone service, or can call the phone company and get an unlisted number (i.e., establish a protected channel of communication).

An information warrior who wishes to undertake denial of service attacks has many techniques at his or her disposal. Some of these are based on logic attacks against specific nodes in a network, some are based on overloading the capacity of links and receive nodes within a network, and some may be based on jamming receive nodes.

The techniques used for denial-of-service attacks vary with the nature of the service being attacked. Furthermore, as networks, their link bandwidths, their transmission codes, their service protocols, and their switch technologies evolve, new techniques must evolve to support denial-of-service attack. Techniques that are effective against specific current networks are unlikely to be effective against

future networks that will eventually supersede them. Therefore, the panel discusses the approach in generic rather than specific terms.

Military and civil networks are generally linked together using a complex ensemble of voice and data links that may include the following:

- Satellite communication,
- Microwave transmissions,
- Undersea cables,
- Copper wire lines,
- Fiber-optic links, and
- Radio broadcasts (high frequency [HF], very high frequency [VHF], and so on).

With varying degrees of ease or difficulty, these links, and the nodes that they feed into, may be attacked—by the physical destruction of an individual segment of the network, by management or political actions, by logic attacks, by saturation attacks, or by noise jamming. The mode of attack is relatively immaterial as long as it denies network and communication service to the adversary.

The concept of physical destruction is relatively straightforward. It may involve anything from cutting wires to the physical destruction of national gateways to a SATCOM system. For such destructive denial-of-service attacks to have a significant value, rather detailed knowledge of the actual topology of the system is required.

In many communication networks the severance of an individual link will have little, if any, effect, because most modern networks are designed to reroute a call automatically to alternate links. For large national networks, the number of alternate paths may number in the billions. Since physical attacks on individual links are unlikely to create a significant problem for an adversary, it is clear that to achieve effective denial of service the proper points of attack are the switches that route messages over the available links. In a national telecommunications network, a relatively small number of switches manage the network. These can be attacked electronically or, if physically accessible, by ordnance.

Electronic attack of the switching computers of a public switched telephone network (PSTN) implies an ability to gain access to such computers. Managers of PSTNs work hard to ensure that their systems are immune to such attack. Sometimes they are successful in their efforts and sometimes not. A current capability to mount a successful attack on a PSTN does not guarantee future success. Maintenance of such a capability requires the continuous detailed tracking of worldwide trends and policies in PSTN design and daily attention of an active cadre of personnel to the development of techniques to defeat the most recent upgrades in protective techniques for PSTN software.

Actual attacks on the PSTN of an adversary would probably be carried out by special operations forces (SOF) personnel whose efforts would have to be supported as appropriate by one or more of the Services. If SOF personnel establish an entry point into an adversary's telecommunications network over a

period of time, the device used for entry should be able to communicate to some central facility (airborne, ship-, or land-based) that can exploit the entry. If the exploitation facility needs to be relatively close to the entry point, then a Navy ship would constitute a platform that can loiter in the area for extended periods of time and perform the needed functions. Long-endurance aircraft (Navy or otherwise) also can perform the needed functions.

When the links of a network involve the use of SATCOM channels, interesting possibilities arise for denial-of-service attacks. Physical attack on SATCOMs may be infeasible because they may be owned by international consortia or by neutral third parties. At present the United States has no antisatellite weapon, and Congress has restricted attempts to develop such a weapon in the past. Additionally, in future conflicts it is quite possible that both the United States and its adversary will use the same satellite, and thus it will be counterproductive to U.S. interests to destroy it.

The approaches that are available for denial of SATCOM services are as follows:

- Administrative and political actions,
- Uplink jamming,
- Downlink jamming, and
- Logic attack.

If feasible, the administrative and political approach is the most straightforward and the one most likely to succeed. The United States might simply go to the nation or corporation managing the SATCOM system under attack and persuade it to deny service to the adversary. This might be accomplished by buying or renting all of the available channels or by using economic and political leverage to induce system managers to deny service.

If the more straightforward approaches fail to work, uplink and downlink jamming may be attempted. Both approaches require that the jammer have a proper geometric relationship to the footprint of the SATCOM. Uplink jamming of early generations of geostationary communications satellites that did not employ narrow beams required only that the jammer be in the same hemisphere with the nadir point of the satellite's footprint. This situation has changed. Commercial SATCOMs are now designed to use multiple narrow beams to permit frequency reuse. In that situation, the geographical location of the uplink jammer must be within the particular beam being jammed. On the other hand, uplink jamming against a low Earth-orbiting SATCOM (e.g., Iridium), which has extremely narrow beams, requires that the uplink jammer be within distances as short as 60 to 100 nautical miles of the satellite's nadir point. Downlink jamming requires the availability of an elevated platform whose footprint must be large enough to cover the entire area to be denied to the adversary. A capability for both uplink and downlink jamming implies that U.S. forces are stationed close to the adversary and are provided with effective protection from physical attack, since they actively radiate.

Given the difficulties inherent in both uplink and downlink jamming, logic attack, when feasible, is the preferred form of SATCOM denial-of-service attack. All communication networks have a number of protocols that determine message routing, class of service, error correction codes, billing information, caller location, and so on. If any one of these items is attacked successfully, the result will be an interruption of communication. One might imagine that an adversary's attempt to communicate via a SATCOM channel might be thwarted by a message saying, "Service denied for nonpayment of bills." Under the rubric of logic attack, the techniques that may be used are limited only by one's imagination.

Whatever nonadministrative techniques are used to achieve denial of service, there is a major role for forward-deployed sea-based forces. Most concepts of uplink or downlink jamming or of logic attack require the availability of LOS access to the target node. In many, but not all, cases of confrontations with an adversary, naval forces will be the only sustainable forces that can achieve such geometries and also protect themselves from hostile counterattack.

Information Warfare—Deception Techniques

The military use of deception probably predated the Greeks' use of the Trojan Horse during the siege of Troy. In modern terminology, any technique that induces an incorrect perception of reality is a form of deception. In this respect, deception is taken to include the following:

- Misleading an enemy by releasing incorrect information (to the media or to the adversary's agents) about our intentions or capabilities;
- Changing or modifying the signature of our platforms and their emissions so that the adversary's sensor reports incorrect information;
- Intruding into an adversary's digital databases to modify the data contained there;
- Usurping an adversary's communications channels and transmitting erroneous information; and
- Inserting false data into enemy sensors both electronically or through the use of decoys.

The first two of these approaches have been used in conflicts throughout recorded history. The value of disseminating false information concerning intentions and capabilities and the value of camouflage need no comment. However, the remaining two techniques represent new capabilities that are the result of evolving technologies.

If an intruder can gain access to a protected domain of a network that contains data, then the intruder may be able to change that data. Success in such an endeavor can have profound effects on military operations—target locations can be changed, data concerning asset inventories and availability can be modified,

call letters and passwords can be changed—again, the damage that can be accomplished and its military impact are limited only by the intruder's imagination.

An adversary who attempts to protect himself against such attack has a serious problem. He can attempt to prevent intrusion with fire walls, routers, frequently changed passwords, and various techniques for electronic verification of the identity of a would-be intruder. Such techniques exist and are in worldwide use by managers of both civil and military networks. Obviously, they are not always robust against new or evolving means of attack. Statistically, we have no reason to believe that the impenetrability of the databases of future adversaries will be any better than the rather dismal track record to date of closely guarded civil and military databases. Given that there will always be a nonzero probability of database intrusion, a data systems manager must develop and maintain techniques for authentication of the database. Basically, authentication can be achieved only by comparing what is in a database with what is contained in one or more replica databases. Error-correcting codes certainly exist and are used routinely. Along with the use of check sums and similar techniques, they provide a significant measure of protection. However, such techniques offer little protection against text substitution attacks on database error-correcting codes, for they cannot tell which is correct. For example, Mr. A weighs 192, 129, or 921 pounds. Logic may imply that it is improbable that Mr. A tips the scales at 921 pounds. However, unless one had a trusted database that had Mr. A's correct weight as an entry, there would be no way of telling if either of the remaining statements is correct. The complexity and cost of such techniques are substantial, and the process of recertification of a database can also be expensive.

An illustration of the difficulty of correcting a database thought to contain erroneous information can be given by a U.S. Navy example. For many years all U.S. oceanographic charts showed a sea mound off the coast of Newfoundland. Shipping avoided the area because the charts showed a water shoal big enough to cause a problem for deep-draft vessels. As evidence accumulated that the sea mound did not exist, the problem of removing it from the database became substantial. First, a new survey was required to establish ground truth, and then all holders of the charts (database variants) had to be informed of the error. The correction of errors induced in a digital database is a similarly complex process, particularly if the errors are small and subtle.

Possibly the most militarily effective approach to the deception of an adversary will be the employment of techniques now available for usurpation of voice and data transmission channels. As a simple example, consider a television broadcast station. If the station could be captured intact, without external evidence of the occurrence, then the broadcasts could continue in the same format on the same channels. But the messages that were broadcast would change. Instead of exhortations to the populace to continue the struggle, tales of military disaster could be broadcast along with comments about the inevitability of defeat.

"Morphed" messages containing a leader's voice and image could be sent out that directed surrender in compliance with U.S. terms for conflict termination.

Whatever techniques are used for deception (and the techniques will change with time), they tend to have a powerful impact on an adversary's will and capability to continue to offer effective resistance. The panel is persuaded that these techniques will be powerful weapons in future conflicts and that naval forces as forward-deployed forces will use them extensively.

Information Warfare—Disruption Techniques

Peacetime experience indicates that most information-processing and transmission networks have little reserve capacity. Indeed, the designers and operators of a system generally fail to understand its instabilities in response to unanticipated perturbations. The problems of system saturation and overload encountered by America Online, when it instituted a new charge plan, were not predicted despite extensive prior computer modeling of the system. The impact of the new pricing plan was difficult to predict because the effects induced were highly nonlinear. The unplanned America Online debacle is an illustration of the impact of nonlinear effects. Even without a purposeful adversary at work, it has taken many months and the investment of hundreds of millions of dollars to rectify the America Online problem.

Information warriors recognize that the effects of disruption attacks on computer networks tend to be nonlinear. As an example, if disruption is achieved by the partial elimination of connectivity within a data network or by the overload of a specific switching node, the network will normally reroute the load through surviving links and nodes. If these surviving links have little reserve capacity or are themselves running near saturation, they will begin to stack incoming data in queues in buffer memories. Eventually buffer memories will overload. Bits will be lost, and as error rates increase, a point will be reached at which error-correcting codes begin to function improperly. In effect, such systems do not degrade gracefully.

Disruption attacks are inherently subtle and if properly executed are difficult to diagnose and rectify. Ultimately, a system operator should be able to find the problem and reconfigure the system to regain functionality. But the process may take a long time and cost a great deal of money. By the time the cause of a disruption is diagnosed and rectified, the conflict may be over. Clearly, disruption techniques are fragile. An individual technique is generally applicable only to attacks on a specific deficiency in a specific system of an adversary. Once used and understood, generic fixes tend to be installed worldwide into all similar systems. The implication is that the offensive information warrior must be engaged in a never-ending quest to find new techniques that exploit previously imperfectly understood system vulnerabilities.

Information Warfare—Destruction

The panel emphasizes that the term "destruction" in D^4E is not limited to destruction by electronic means. The physical destruction of a node in an adversary's information system will be an effective means of offensive IW provided that it does not cause unacceptable collateral damage. When the node is a discrete targetable object such as a large satellite dish that serves as a national gateway antenna, attacks with ordnance are an extremely effective IW response. On the other hand, when the node is a computer whose location cannot be established by conventional means, attack by the electronic techniques of IW may be the only feasible approach.

When used in association with IW attack, the term "destruction" usually implies the destruction of databases, perhaps by insertion of either an erase command or malicious software that destroys all accessible data files. Such destruction might be reversible, though, if the database were properly backed up and/or protected from attack by physical separation (air gap) from a network under attack. Capabilities for attack on digital databases are, of course, not effective against databases stored as hard copy (paper) files. In effect, the value of database destruction (assuming that network access is feasible) is to force the adversary into a mode of operation that either is paper based or is limited by the requirements for frequent or even continuous backup.

On the other hand, if the destruction is accomplished by the insertion of malicious code, then before backup databases can be reloaded the adversary must find the source of the problem and purge it from the system. Ridding a computer of a virus can be a time-consuming process. In effect, destructive attacks, although reversible in their impact, can result in extended periods of network outage that can lead to critical systems being down during times of U.S. attack.

Other forms of attack that lead to the physical destruction of computers or electronic systems are conceptually possible. One can conceive of the insertion of malicious code that will attack and damage the central processing chip within a computer. Alternatively, if a high-voltage transient can be caused to pass through the surge protectors on the power lines of a computer, there is a real possibility that the internal components of the computer will be destroyed. Destructive attacks using these classes of techniques are likely to be applicable only to specific computer and network configurations at specific times. For example, if attack through surge protectors were to become a serious problem, then new technologies that provide more effective surge protection would be expected to evolve rapidly.

Although the techniques for destructive attack may not prove to be robust indefinitely, appropriate tools for such attacks should be developed so that the vulnerabilities of specific networks and computers can be exploited. As new defenses evolve in the target set, new means of destructive attack should be developed.

Information Warfare—Exploitation

Although Henry Stimson, when he was secretary of state, once remarked that "gentlemen do not read other gentlemen's mail," the United States and all foreign governments exploit whatever source of information is feasible to exploit. The United States conducts active national programs to collect, analyze, and exploit all appropriate foreign information. Since these programs are national-level programs, the U.S. Navy, along with the other Services, provides support for them but is not responsible for their overall management.

The military value of exploitation of an adversary's information and communication systems is incalculable. A real-time ability of U.S. forces to intercept orders from an adversary's senior commanders to subordinate commands will in some circumstances allow U.S. forces to take actions that can negate the adversary's intentions.

The development of an enduring capability to exploit an adversary's databases and communications channels is an immensely difficult, ongoing task. Naval personnel have made distinguished contributions to the development of exploitation capabilities and have had responsibility for the continued operation of such systems. The panel has no reason to assume that the Navy's traditional role in national exploitation programs will change during the next 25 to 35 years.

Information Warfare—Summary and Recommendations

As discussed in the preceding sections, the five functions (D^4E) of offensive information warfare can, if implemented effectively, have highly leveraged effects on the outcome of confrontations. The Navy is a player in this world, and the panel has every confidence that, for the foreseeable future, it will continue to be an effective practitioner of offensive IW.

Because the techniques of IW are, and will continue to be, in a state of evolution, the panel cannot recommend specific programmatic directions for investment. These directions will be, and must continue to be, responsive to future evolution of the technology of data storage, protection, and transmission.

The panel presents the following suggestions:

- Efforts should be made to make operational naval commanders fully aware of the military implications of the techniques of offensive IW.
- A general realization should be established throughout our naval forces that the techniques of offensive IW are symmetrical. If there are specific vulnerabilities in U.S. systems, our adversaries can exploit them with disastrous consequences. Defensive IW capabilities may become as important to the U.S. Navy as CMD or TBMD.
- Success in offensive IW will correlate with past investment in both people and in the development of techniques. People must be trained to understand the complexities of the field. In effect, IW must be recognized as a naval career

specialty. The funding priorities for the development and procurement of IW weapons must be considered to be coequal with the funding priorities for other weapon systems.

INFRASTRUCTURE ATTACK

Background

During World War II, Allied forces attempted to destroy Germany's ability to wage war by a sustained and massive series of bombing raids aimed at the destruction of the infrastructure of the German economy. Although these raids did not in themselves destroy the German infrastructure, over a period of several years they certainly weakened Germany's ability to prosecute the war.

Postwar surveys indicated that the main reason the bombing campaign failed to achieve its objectives more rapidly was that the weapons used in that campaign were not appropriately designed for the purpose. Most weapons dropped on Germany in World War II were bombs and incendiary devices. The dispersion associated with World War II bomb delivery meant that, statistically speaking, the critical elements of an individual factory or other economic activity were rarely destroyed or damaged. If damaged, the target frequently could be made operational again in a relatively short time.

Prolonged wars of attrition are unattractive options to the U.S. public. Techniques for infrastructure attack will be attractive if, and only if, they contribute demonstrably to the rapid collapse of an adversary's military resistance.

Modern Theories of Infrastructure Attack

Modern theories of infrastructure attack start with the premise that the physical and civil structure that supports a nation's economy is a network of nodes and services. The argument is made by proponents of infrastructure attack that when critical nodes and links are rendered inoperative, there is a cumulative effect that rapidly leads to a substantial disruption of a nation's civil, political, and ultimately military functions. In such theories, a nation's electrical and power distribution system is assumed to be central to the functioning of a modern economy. If special weapons or other techniques are available to damage the power grid in ways that are not easily reversible, the victim of the attack will be at a serious disadvantage. Similarly, the argument is made that the destruction of critical transportation nodes such as bridges and tunnels will prevent or severely limit the internal transport of food, raw materials, and military equipment. Thus, it is argued, if weapons or other destructive techniques are designed for the specific purpose of eliminating critical nodes and links in a society's infrastructure and if these nodes and links are targeted selectively, then a conflict can be brought to rapid termination. Identification of the vital nodes or umbilicals of a key facility

(manufacturing, C^4I, and so on) coupled with a precision weapon carrying the appropriate lethal mechanism can be an extremely effective end-to-end system construct. It minimizes collateral damage and subsequent reconstruction, while eliminating a key capability.

Upon review of many of the weapons and techniques currently under development by the Navy and other Services, the panel believes that many of them will lead to a robust Navy capability for selective and effective attacks on an adversary's economic infrastructure and on its will and ability to sustain resistance. The panel has every reason to believe that these techniques will be used extensively by naval forces as their contribution to the rapid termination of a conflict.

The use of military capability to eliminate resistance will inevitably need to fit into a larger political and national security context. Military actions, threatened moves, or perceptions of military capabilities will be the most important components, but not necessarily the only ones. The desired impact is likely to result from cumulative and varied activities that are tailored to a specific opponent. Traditional military tasks fulfilled with rapidity and brilliance, such as control of the sea and air and seizing and holding territory, will help to destroy the adversary's will to resist. A capability to force a rapid and significant alteration of the national will of an adversary will in all likelihood also require other actions that fundamentally and directly threaten a nation's, or its leadership's, ability to survive.

In certain circumstances, threats to U.S. interests may be deterred if potential adversaries recognize that the United States has a credible capacity for the rapid imposition of unacceptable conditions on their constituencies. However, for deterrence to work, there must be a belief that the United States has both the capacity and the will to unleash its capabilities to cripple an adversary's infrastructure.

Desirable Capabilities for Infrastructure Attack

Each future conflict situation is likely to be unique. Therefore, it will be necessary to draw from a range of capabilities tailored to the specific situation and targeted at those areas identified as likely to affect the will of a given adversary.

General

Although a number of new or existing capabilities may be useful in carrying out infrastructure attacks, the development of a capacity to undermine the national will of adversaries needs to be pursued as a specific objective.

The direct ability to disarm, destroy, and control an adversary's military capabilities with minimum casualties and collateral damage and awesome effi-

ciency is fundamental to most major regional conflict (MRC) contingencies. But capabilities also need to be developed to optimize the application of infrastructure attack so that the adversary's national will to continue a conflict collapses rapidly.

Two sets of capabilities will be required—capabilities for attack on the broader infrastructure and capabilities specifically required to destroy an adversary's military capability. However, there exists an overlap in the requirements for accomplishing these two aspects of affecting an adversary's will. In the case of military capabilities, there is a natural evolution toward developing a more advanced force and less emphasis on requirements that extend beyond force-on-force engagements. It is a matter of shaping the force through an acceleration in certain primary areas and of putting emphasis on systems that produce information, rapidity, brilliance, and control.

There does not appear to be today an equivalent to the Cold War emphasis on strategic and nuclear weapons. Nonetheless, certain extraordinarily dominant capabilities still may be needed. Such post-Cold War strategic systems might produce controlled chaos or help achieve total control in a situation. Both chaos and control could be important components in denying what is valued most by an adversary. Ideally, these new capabilities and techniques would provide, at least cumulatively, the potential impact of nuclear weapons without causing massive casualties or widespread destruction.

Leadership Attack

Making an adversary's leadership feel directly vulnerable could be important in certain situations. However, there may be political or legal constraints in some cases. Systems are needed, nonetheless, that can provide reliably the locations of principals in real time. There is also a need for weapons that can penetrate with precision likely leadership locations in a range of environmental conditions. Vulnerability can also be created by other means such as cutting off, or selectively disrupting, leaders' means of communicating among themselves, with their military, and with their public. In some instances, simply knowing what the leadership is saying in secret communications may provide exploitable clues.

Creation of an Atmosphere of Fear and Uncertainty

Creating massive disruption and confusion in the general public may add to the pressures on a leadership to capitulate. This atmosphere may result from repeated pulses of noise, light, and massive shock waves and reverberations as military and other economic targets are systematically destroyed. In other instances, precise actions within an urban area such as destroying key bridges, turning off the electricity, or rendering a sewerage system inoperative may suffice.

Information Dominance

The panel believes that IW will prove to be one of the most important techniques for infrastructure attack.

The disruption of communications should add to the cumulative psychological impact of a campaign against an adversary's infrastructure. The capacity to achieve electronic isolation of a country or a specific part of it may help create a loss of will. The panel believes that a capability is needed to disrupt, destroy, and control the various means of communications within both the military and public sectors and to cut off communications externally. For example, severing telephone links will have both practical military and psychological impact. Even if all military or secure systems, which are likely to be redundant, cannot be suppressed, loss of the public telephone system will have a significant impact in many societies. When radio, television, and other sources of information also can be denied, the resulting information blackout can have telling psychological consequences for the leadership and the general population.

In modern countries, the means to disrupt financial networks, computer systems, and the Internet or to intrude into other areas of cyberspace may be important. The development of an ability to intercept or cut off communications to terrorist networks or units that could implement offensive missile or WMD (nuclear, chemical, and biological) attacks should be accorded high priority.

Traditional military requirements to intercept, read, and exploit leadership and military communications will still be important. This may be more difficult to accomplish, however, as secure capabilities proliferate and become more sophisticated. What is said in open communications such as those on the Internet, on cellular phones, or in exchanges of electronic mail internally in a country also may provide important clues. With the proliferation of technology, interception and decryption will be an increasing challenge. The rapid multiplication of means of communication will require rapid sorting out and dissemination of key information. Reaching the necessary level of proficiency may require new technological breakthroughs.

Psychological Warfare

The ability to send carefully orchestrated messages to an adversary's populace on radio or television will be an important way of conveying information selectively in what is likely to be a chaotic situation. Deception, even if achieved only for short periods, may be of great utility, especially with regard to military operations.

Video and Voice "Morphing"

The potential impact of psychological operations (PSYOPS) has increased substantially with the evolution of modern computer techniques for creating vir-

tual reality. These techniques have been used extensively in the American entertainment industry. Since an adversary's leaders give many speeches over radio and television, billions of their phonemes are available, along with many images of them delivering talks or engaging in other activities. Modern computers provide the capability to construct speeches, using an adversary's own phonemes, that advocate capitulation, admit guilt or malfeasance, or provide orders that are inimical to the adversary's interests. A television viewer or a radio listener would have no means of knowing that such a message was synthetic. The implications of use of such techniques and their potential impact on an adversary must be better understood than they are currently. They may, in fact, constitute one of the most potent means of infrastructure attack available to U.S. forces.

Immobilization of Transportation Systems

Improved capabilities are needed for shutting down transportation both externally and internally and for helping to build an adversary's feeling of being squeezed in a steel vise. A paralysis of transportation should be sweeping in scope and imposed with the maximum possible speed. The panel believes that smart mines (perhaps using nonlethal weapons), electronic attack, and other techniques specifically designed to freeze commercial traffic or halt military movement are feasible to develop and operate.

Weapons can be developed that will in effect curtail movement in and out of an adversary's territory, either totally or selectively. Systems can be developed that are able to shut down airports for sustained periods, close seaports, stop rail networks, and prevent trucks and cars from moving across borders. The impact should be nearly total and of long duration. Improved techniques can be developed to achieve a complete cutoff of the import and export of goods, the movement of people, and reinforcement by friends. Countries dependent on external lifelines may need to be isolated totally.

The effect of infrastructure attack will be enhanced if means are developed to paralyze transportation within a country—either totally or selectively. For example, transportation modes could be denied sequentially or a particular city could be totally disrupted nearly simultaneously. This would help bring home a message of its helplessness to the general public and in practical terms could impede the economy or the movement of military forces around the country. This approach would include disabling trucks, trains, automobiles, small aircraft, boats, and the like.

Even a more limited and selective capacity to disrupt transportation would be useful in some circumstances. For example, the ability to disable vehicles that violate a curfew or are moving arms within a city would be invaluable in an urban control situation. It might be desirable to develop the capability to stop suspect vehicles without injuring the occupants or destroying the cargo. Selective disrup-

tion would also have utility where U.S. forces were trying to arrest specific individuals and avoid injuring innocent civilians.

Denial of Power Generation and Distribution

Although military units are usually equipped with auxiliary motor generator sets, taking out some or all of a national network for electrical power distribution can have a devastating impact on military operations, on the local economy, and on the general populace. Extending the blackout to other power generation systems such as natural gas facilities, diesel generators, and large power plants would add to the effect.

At the onset of the Gulf War, Iraqi power generation and distribution systems were among the first targets attacked. These attacks were remarkably effective in crippling civil and military operations in Iraq. They certainly brought home to the general populace the overwhelming capabilities of the United States. The panel believes that maintaining and evolving the capabilities to undertake this type of attack will be a crucial component of future U.S. abilities to force an early resolution of conflicts.

Economic Assault

A demonstrated ability to knock out factories, oil refineries, and other productive sectors of the economy could add to the pressures for capitulation, contribute to discontent among the populace, and begin to diminish economic power. Modern precision weapons afford the capability to destroy the one or two critical components (e.g., the power transformers that feed the factory) that allow a factory or refinery to function, without the need to demolish the entire plant.

The panel believes that a capacity should also be developed to deny service industries as well as traditional industrial targets. Economic capabilities may be what an adversary's leadership values most. In other circumstances, it might be more effective to carry out destruction selectively as an indication of what could happen (e.g., one oil field or refinery a day), rather than massively.

Summary

The panel is persuaded that well-conceived and rapidly executed attacks on an adversary's infrastructure will have a substantial impact on an adversary's willingness to terminate a conflict on terms that are acceptable to the United States.

The military capabilities, weapons, and techniques that are needed are as follows:

- Identify and target with precision the critical nodes and links in the adversary's civil structure;

- Deliver weapons accurately or execute specific techniques that destroy only the target of interest and importance;
- Isolate the adversary's military forces from support of the civil sector of society;
- Achieve total information dominance; and
- Effectively attack the will of the adversary's populace and leadership to continue a conflict.

The capabilities summarized here will be used as appropriate by theater CINCs to achieve conflict resolution as rapidly as is feasible. The weapons and techniques discussed in the preceding paragraphs certainly are not and will not be unique to naval forces. However, to provide future CINCs with the tools necessary for effective infrastructure attack, naval forces must be equipped with the necessary tools and techniques and be trained in their use.

The panel suggests that naval forces do the following:

- Develop a cadre of personnel who are knowledgeable in the principles of infrastructure attack and who understand the tools needed for such attacks.
- Be equipped with precision weapons and appropriate warheads needed to destroy critical nodes and links in infrastructure networks.
- Be trained and equipped to take such actions as will assure immediate information dominance whenever required.
- Establish robust connectivity with National systems and organizations that identify the specific critical nodes that must be attacked.

MINES

Background

Land and sea mines have long been in the operational inventory of military forces worldwide. Mines are weapons that wait. Sometimes they wait for many years, until they are triggered by the detection of a predetermined signature or by direct contact with their victim. Regrettably, in the case of land mines they often remained half buried and undetected until years later when, long after the cessation of hostilities, some innocent person steps on them with fatal consequences.

In the past, mines were (with the exception of CAPTOR-like devices) essentially point-contact devices. At best, they were triggered by some attribute of the victim's signature at a maximum range of a few tens of meters. Anyone wishing to traverse a suspected minefield (land or sea) was faced with the probability that crossing the minefield without casualties was less than unity. The options were either to hunt out and subsequently avoid and/or remove the mines or to penetrate the field and accept the casualties that occurred. There are many examples where a local commander decided that minefields were not dense enough to cause enough attrition of his forces to warrant a delay in crossing the field.

Projected Evolution of Mines

The projected evolution of land mines will be determined, to a large extent, by national decisions as to whether they are inhumane devices that are both inappropriate and unnecessary as weapons. Simple antipersonnel land mines certainly may be considered to be in that category. Because they are extremely difficult to clear, derelict land mines have caused hundreds of thousands of civilian deaths after cessation of conflict.

Decisions about the future of land mines will be complicated because land mine technology has advanced far beyond the simple antipersonnel mines of past years and gives promise of transforming mines into potent military weapons.

Although sea mines do not have the same lethal legacy problem as land mines, they do present a major postconflict removal problem. Although even antiquated mines that were designed more than a half century ago have proven to be extraordinarily lethal as a military weapon, the major limitation of sea mines has been their relatively limited range of target detection and response.

Modern technology can transform both land and sea mines into vastly more effective weapons than they have been in the past. Although the development of new mines has not been a matter of high priority within the DOD, technology advances in other fields are easy to incorporate into the development of new mine capabilities. Specifically, the panel notes the following trends in mines:

- Low signatures that makes mines hard to detect,
- Computer controls that make them difficult to sweep using influence (false signature) sweeps,
- Use of low-cost distributed networked sensors that allow them to detect and classify targets at significant ranges (hundreds of meters versus tens of meters),
- Communications capabilities between mines and distributed sensors that permit the optimum management of available weapons, and
- Propulsion systems that allow a warhead to attack and pursue its victim once the victim has been detected.

The first item on this list refers to the current worldwide application of primitive stealth technology to the design of new mine canisters. Sea mines are at best difficult to detect. If the acoustic back-scatter cross section of a sea mine were reduced by as little as 12 dB, the detection range would, in a noise-limited system, be cut in half. This would greatly increase the time for search and would force the search platform to come sufficiently close to the mine as to put it in danger of triggering the mine. The panel observes that the rather limited reductions in acoustic back-scatter cross section achieved by canister shaping could be increased significantly by the use of acoustic absorbent coatings.

The impacts of the next three items on this list are discussed in the next

section. The technology implied by the last entry on this list has been incorporated into the design of the CAPTOR mine and various Russian equivalents. The CAPTOR mine is a tethered canister that, on the detection of the signature of its victim, releases a Mk-46 torpedo that runs down its victim. In the future, the Mk-46 weapon is likely to be superseded by a faster, longer-range, and more lethal weapon.

Designs have been proposed to transform current point contact land mines into weapons that defend a significant area. In these designs, the mine (or some remote sensor) detects the signature of its victim, causing the mine to fire a mortarlike device that projects another device to an elevated altitude. In some design variants the projectile deploys a parachute and uses IR and/or an acoustic sensor. When its victim has been detected, the parachute is cut free, a small rocket is fired, and a warhead is driven into the target. In effect this concept takes existing designs for the BAT weapon and transforms it from a submunition on a missile to a projectile fired by a remotely triggered mortar. Although designs of this nature currently may not be operational, all the components described do exist. In effect, land mines can be transformed into devices that create barriers that effectively inhibit the movement of tanks, trucks, and personnel.

Minefield Technology

An individual mine as a single isolated weapon is not a serious threat to naval forces. Minefields that contain many randomly scattered but uncoordinated mines are a more substantial threat to any force caught in the minefield. If the minefield were designed as a weapon set that was controlled by a networked sensor system, the threat would become significantly more formidable than the threat posed by past minefield configurations.

Modern concepts for minefields are such that attempts at penetration should (until the number of mines has been depleted by effective kills) result in high levels of lethality for the intruding force. The current and anticipated trend in minefield design is to depend on distributed and networked sensors that actuate mobile mines. In an undersea minefield, the sensors might be linked by acoustic modems. In a battlefield minefield, the sensors might be linked by IR, RF, or HF acoustic links.

In a statistical sense, distributed sensors would provide redundant coverage of 100 percent of an area when an attempt was being made to deny the adversary passage. Networking of the sensors would permit detection, location, and tracking of the penetrator. When the data-processing devices that control the weapons in the minefield "decided" that the penetrator warranted being attacked, a prepositioned mobile weapon would be released to attack the target. Underwater, the weapon might be a high-speed rocket or torpedo. On the battlefield, the weapon might, as pointed out above, be rocket or mortar propelled.

Sensor-networked minefields could negate the value of influence (false signature) sweep techniques. When a signature, whether false or real, is detected by many sensors in a network, its location is tracked and various of its aspects (radiated acoustic noise, magnetic field, pressure signature) are compared. If the signatures and track are incompatible with those of a valid target, the mines in the field will not be induced to fire.

The effectiveness of a minefield that is controlled by networked sensors would be extremely high. For example, it could be used to blockade an enemy's naval forces in harbors and to interdict the enemy's seaborne commerce. To the extent that absolute denial of seaborne commerce and denial of the use of naval platforms contribute to limiting an adversary's ability to continue a conflict, minefields that are controlled by networked sensors will become an effective future weapon system in the hands of the U.S. Navy.

Summary and Recommendations

The panel recognizes that the technology of mines is understood and used worldwide. The United States does not have and, without a sustained major investment, will not have a major advantage in mine warfare.

From the standpoint of protecting U.S. forces from the limitation placed on their movements by mines, the prognosis is not good. Various feasible improvements to mine technology such as those discussed in this section can serve to constrict the operations of naval forces both at sea and on land. The panel recommends that a response to these potential limitations above and beyond the development of mine hunting and sweeping be considered. All evidence indicates that although U.S. naval forces can be competent in these techniques, they are unlikely to ever develop a robust advantage that allows them to ignore this threat.

The panel believes that the employment of offensive minefields by U.S. forces has not received the attention its military potential seems to warrant. The problems that naval forces would encounter in negating modern mines and minefields would be as great or greater for an adversary. In some cases an adversary will not have any capability to negate such fields and will be forced to accept the blockading or channeling effects caused by hard-to-sweep minefields.

Based on its assessments of future developments in mine warfare, the panel offers the following suggestions:

- The value and potential of the offensive employment of modern mines and minefields should be incorporated more fully into U.S. doctrine.
- The development of mobile mines that provide area coverage should be supported.
- Concepts for minefields controlled by networked sensors should be explored along with techniques for signature reduction.

URBAN WARFARE

Background

Recent studies by the Defense Science Board (DSB)[1,2,3] have concluded that without significant changes in current weapons and sensors, warfare in built-up or urban areas will continue to be difficult to execute and will probably continue to result in significant casualties among the attacking forces. Urban buildings are, in effect, natural fortifications. The destruction of individual buildings by bombs or artillery generally serves to create additional rubble and de facto to improve the strength of defensive positions.

Neither this panel nor the DSB foresees any single or simple solution to the many problems associated with urban warfare. Present and foreseen technology does allow one to hold out hope that over the next 25 to 35 years, new sensors and weapons will be introduced that will provide considerable advantage to attacking forces.

New Techniques and Devices for Conflict in Urban Areas

Sensors

Evolving technology should produce significant advances in the area of sensors that are adapted to urban combat situations. An ability to see what is in the next building or is lurking at the next intersection without exposing our own personnel to hostile fire would be of critical importance in an urban combat situation. Contemporary technology permits the development of IR, optical, and acoustic sensors that are mounted on small, lightweight, programmable mobile machines (robots) with sufficient connectivity to allow report-back of the images seen. Structure-penetrating radars have been pursued in the past with limited results. However, new technological developments are under way that may provide this capability. The panel believes that it will be possible to develop sensors mounted on small robotic devices that can tell forces engaged in urban combat who or what is in the next room or in the building across the street. Sensors could also be developed that would locate the position of a mortar in defilade behind buildings or a sniper by the detection and tracking of a projectile's

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[1]Defense Science Board. 1994. *Summer Study Task Force on Military Operations in Buildup Areas,* Office of the Under Secretary of Defense for Acquisition and Technology, Washington, D.C.

[2]Defense Science Board. 1996. *Task Force on Information Warfare,* Office of the Under Secretary of Defense for Acquisition and Technology, Washington, D.C.

[3]Defense Science Board. 1996. *Task Force on Tactics and Technology for the 21st Century,* 3 volumes, Office of the Under Secretary of Defense for Acquisition and Technology, Washington, D.C.

trajectory, by use of the detection of UV flashes associated with muzzle blasts, or by the acoustic signature.

New Weapon Delivery Techniques

Although sensors will help locate hostile military forces, weapons or explosive emplacements are needed to drive out the defenders. In urban combat, simple explosives are used to create passages through walls that partition the individual buildings in a city block. Once off the streets, and into buildings, attacking forces clear defending personnel with automatic rifle fire, smoke, and concussion devices.

The availability of weapon-carrying miniature UAVs should make a huge difference in combat in built-up areas. A miniature UAV that can fly through windows and deliver concussion grenades to adversaries inside a defended building should contribute to the rapid reduction of resistance. One might also imagine the design of miniature UAV vehicles that perch on windowsills of defended buildings and are programmed not to attack until they sense the presence of defenders.

The panel believes that in the future, robots—or more properly speaking, programmable mobile machines (PMMs)—will be used to cross the next street, enter the next block of buildings, and emplace explosives against critical structural support columns or detonate concussion devices that will stun, blind, or kill the defenders.

Other devices that allow rapid breaching of concrete barriers and tunneling under streets and beneath buildings will also allow the placement of explosive charges that will destroy strongly defended structures that cannot be cleared without excessive casualties.

Less-than-lethal weapons may become very important in the conduct of urban warfare. They generally do not require line of sight and yet can be somewhat directional in their effects. They also remove the specter of harm to innocents that may be caught in the hostilities.

Summary and Recommendations

In general, the panel believes that the first principle of urban warfare should be to avoid it, if at all possible. For those situations where urban conflict cannot be avoided, the panel believes that the capabilities to use improved robotic sensors, concrete breaching and tunneling devices, and robotic emplacement of explosives at structural members should improve significantly the future capabilities of naval forces to undertake and win battles in urban areas. Utilization of nonlethal weapons may have an important role in urban warfare.

The panel suggests the following:

- Sensors and PMMs should be developed that allow accurate and efficient target designations in urban areas and risk-free remote placement of explosives or nonlethal weapons.
- Naval forces likely to engage in urban combat should develop improved tactics and doctrine based on employment of improved sensors, lethal miniature UAVs, and PMMs.

9

Sea-based Nuclear Weapon Alternatives

BACKGROUND

The U.S. Navy currently operates a dedicated force of nuclear submarines (SSBNs) equipped with long-range ballistic missiles with nuclear warheads. As this force ages over the next 30 years, it will need to be phased out and replaced if a national decision is made to continue the sea-based deployment of nuclear weapons. The panel believes that if the United States elects, for political as well as military reasons, to replace the current sea-based nuclear force as it is phased out of service, the weapons selected and the platforms used to support those weapons will be significantly different from the warhead delivery system currently in operation in the Navy's SSBN force. Current U.S. policy is not to develop new nuclear weapons. However, one-for-one replacements of existing weapons from blueprints is difficult because the availability of certain materials changes with time.

The design of the current force was driven by the requirement of having an invulnerable deterrent force that could reach targets in the former Soviet Union 5,000 to 6,000 miles away with an accuracy within 0.25 mile, based on guidance and targeting technology of the 1970s. Many things have changed since the architecture of the SSBN force was established. The primary target set, which was remote Soviet nuclear weapon silos and support centers, is diminishing and may disappear in time. There is currently an understanding for the United States and Russia to "de-target" each other. The panel believes that over the next 25 to 35 years the need for a U.S. nuclear deterrent will continue and that the primary targets for sea-based nuclear weapons will continue to be hardened, or hard to

destroy, sites where adversaries store chemical, biological, and or nuclear missiles and warheads.

Destroying hardened, or deeply buried, targets will warrant and require special types of weapons. To some extent, the weapons employed against this target set will depend on the attributes of the hardened or buried target. Once a target has been located and identified, including its vital nodes, there is a logical hierarchy of attack to be considered. This could be embodied in a doctrine giving the following order of options: (1) conventional weapons attack on externalities or umbilicals (air intakes, vents, entrances/exits, communications, power sources, and so on); (2) a direct attack using either a high-velocity precision penetrator containing a lethal mechanism (explosives, thermite, and the like) or a large multigigajoule kinetic energy earth penetrator); and (3) an earth-penetrating weapon with a yield tailored to hardness.

The B-61 Mod11 satisfies some but not all of these requirements. In principle, an already developed and tested nuclear artillery shell could be packaged into a penetrating munition to conduct such a mission. It would not require a nuclear test but would require testing to assure integrity and functionality after earth penetration. The technology for more optimum designs requiring smaller quantities of fissile materials is also known but would probably require nuclear testing.

Currently, the United States has a self-imposed ban on nuclear testing and the introduction of new nuclear weapons. The national leadership may have to decide on whether to have either plans on the shelf or a special, small-yield nuclear weapon to conduct a preemptive interdictions attack on a high-value target such as a WMD production or storage facility that is hardened and deeply buried. An alternate policy would be to conduct a retaliatory strike if U.S. forces, population, or interests are attacked by enemy WMD. The current nuclear stockpile would create a great deal of damage and collateral effects that certainly can threaten a state/nation responsible for an attack against U.S. interests. However, the consequences of such a retaliatory massive response could inhibit the U.S. willingness to conduct such a mission.

Weapons can now be, or will soon be, guided to their target with essentially zero miss distance, diminishing the need for nuclear weapons with high yields. High-accuracy, low-yield weapons should be sufficient to destroy most future targets whether buried, hardened, or remaining in hardened silos. The missiles needed for the accurate delivery of such warheads can be significantly smaller that the current D-5 missile on our SSBNs, and shorter range (1,000 km or less) for a Navy involved in littoral warfare.

No decision has been reached at this time on the configuration of the architecture for future sea-based nuclear forces. The next generation of sea-based nuclear forces may be a simple replication of the current SSBN force, with long-range missiles capable of delivering warheads to the same or greater range than the D-5. Alternatively, new or other sea-based platforms, including submarines, may be built to launch tactical nuclear weapons only, or the distinction between

tactical and strategic targeting may fade leading to the deployment of general-purpose submarines capable of launching a variety of long- and short-range ballistic and cruise missiles.

ARMS CONTROL ISSUES

The demise of the Soviet Union has led to significant changes in the strategic nuclear policy and programs of the United States. No longer are U.S. strategic missiles and aircraft on high alert and aimed at targets in the former Soviet Union. Bilateral arms control agreements with the former USSR and with Russia over the past decade have eliminated the deployment of a majority of all operational strategic and theater nuclear forces (see Appendix B).

START I has reduced the number of all strategic warheads to 6,000 or fewer for both the United States and Russia. After the INF Treaty and START I, relatively few theater nuclear weapons remain deployed. Deployment of theater ballistic missiles with ranges greater than 600 km are banned on surface ships. If START II is ratified, the number of strategic warheads allowed each side will be 3,500 or fewer. START II reductions were originally intended to be completed before 2003 and limited the number of deployed SLBM warheads to 1,700 to 1,750. If START II is eventually ratified, follow-on bilateral negotiations for START III could seek further reductions to about 2,000 or fewer total warheads for each side.

The panel cannot predict how bilateral arms control negotiations with Russia, or related multinational negotiations, will proceed over the next 25 to 35 years in reaching further nuclear arms reductions or restrictions; nor can it predict whether new threats will develop elsewhere as a result of the proliferation of nuclear weapons and other weapons of mass destruction or because of a nuclear-armed China or what new U.S. doctrines for nuclear weapons or for deterrence purposes will evolve. There is a reasonable belief by the panel, however, that the need for some strategic nuclear forces will continue well into the next millennium as an element of U.S. national security policy. If this is true, we expect the Navy may have a major responsibility for maintaining all or much of that force at sea. It would follow then that the Navy should prepare to replace existing D-5 missiles, their nuclear warheads, and the Trident SSBN before the year 2035.

If START II is ratified, all ICBMs equipped with multiple independent reentry vehicles (MIRVs) (but not SLBMs similarly equipped) will be banned. The panel is not certain, however, what should replace the current D-5 missile, what its targets could be, and what size warheads it should be capable of delivering—whether or not START II is ratified. This is more properly a role for the Strategic Communications Command, and one that is likely under way. The panel believes, however, that the Navy should begin considering what appropriate options for the nuclear warhead size and range for a new SLBM might be and, therefore, what type of relatively invulnerable submarine platform it should have when current Trident submarines and their D-5 missiles are retired and/or replaced over the next decades.

WEAPONS FOR HARD OR DEEPLY BURIED TARGETS

Beyond the need for a strategic nuclear deterrent, there are other worrisome trends where nuclear weapons may have a unique and important and, perhaps, provocative mission best delegated to the Navy for implementation. There is concern that countries antagonistic to the United States are implementing long-term programs to bury and harden many important military targets that can make effective U.S. Navy force projection doctrines more difficult and risky to pursue. How extensive these programs will be is uncertain, but it is clear that at least North Korea, Iran, Libya, and Iraq use mountain tunnels with multiple entries to hide and protect weapons and equipment of all kinds. These countries are also constructing deep underground bunkers to house important national and military command and control centers and WMD storage sites, some apparently beyond the reach of current conventional precision-guided bombs and missiles. In 30 to 40 years, the numbers of these hardened and buried sites are expected to increase significantly and may include critical industrial as well as military activities. Concepts being considered for high-velocity earth-penetrating weapons are predicted to be capable of reaching targets buried a few tens of meters in soil.[1] Concrete bunkers buried a few tens of meters and tunnels buried more than 100 meters deep are likely to remain beyond the capacity of conventional penetrating warheads to destroy or incapacitate.

An issue for the Navy and the Nation to contemplate, then, is whether it would be prudent to pursue the development of highly accurate, zero-CEP penetrating weapons and low-yield nuclear penetrating weapons, perhaps with warheads that have yields less than 1 kt. Such weapons would be designed to penetrate sufficiently deeply through earth and rock to destroy deep bunkered sites that are buried many meters more deeply than can be credibly destroyed with precision-guided conventional weapons. A nuclear weapon with a 50-ton yield would probably need to be designed to penetrate nearly 50 meters below the surface to avoid venting radioactive gases. Tradeoff studies between weapon impact velocity, penetration depth, weapon yield, and accuracy versus target hardness and depth should be performed to determine how effective nuclear penetrating devices could be.

Extensive underground tunneling that is difficult to locate from above ground will be difficult to destroy even if conventional weapons could penetrate deep enough. A conventional penetrating weapon, if it penetrated sufficiently deep with a few hundred pounds of HE, might damage a small segment of a tunnel complex. A nuclear penetrator with a yield of 50 to 100 tons of explosive power might be able to destroy all or a significant portion of that underground complex at a comparable depth of penetration. Awareness of U.S. nuclear penetrators could drive enemy tunneling even deeper with ever-increasing costs and with

[1]Rigali, Don. 1996. "Prompt Strike and Earth Penetrating Weapons," presentation to the Panel on Weapons, Sandia National Laboratories, Albuquerque, N.M., July 9.

greater difficulty to use. The United States does have a penetrating weapon designated as the B-61 Mod 11. This weapon was intended as an interim design and, at the time of design freeze, did not incorporate all of the attributes that might be considered desirable to support the concept of the operations considered here. Future nuclear penetrating weapons can be designed (as modest modifications of nuclear devices developed in the past) that may be able to penetrate to depths that avoid venting and fallout. The panel recognizes the many political and operational problems associated with producing and using a new nuclear weapon. A policy of no-first nuclear use, radioactive fallout from venting, and possibilities for collateral damage are all factors that may inhibit the use of a nuclear device by U.S. forces in the future.

Unless alternative methods are found to destroy such facilities, particularly WMD storage facilities, however, naval and Marine force projection missions in the future could be constrained or precluded. If special nuclear penetrating weapons are available, it will be a matter for the national leaders to decide whether to use them preemptively or in response to attacks with WMD. Conventional weapons would be easy to justify in a preemptive attack against an enemy's WMD sites, and the use of nuclear penetrators perhaps more readily justified and supported politically if U.S. and allied forces and populations became casualties to a WMD attack from that enemy nation.

Alternative measures to deny effectively the use of deep bunkered sites should also be considered, including the bombing of entrances and exits, air-conditioning vents, generators, and communications connections and other umbilicals, assuming these are near the surface and can be located. To avoid attack, however, bunker entryways and air-conditioning vents could be camouflaged, co-located with civilian activities such as hospitals or factories, and located where attacks with any explosive-type weapons could cause large-scale collateral damage and civilian casualties. This ploy was used by Iraq in Desert Storm. Further civilian casualties could be caused by the seepage of CBW agents from a bombed-out storage bunker. There is concern that U.S. forces during Desert Storm may have suffered such exposure. Consideration should also be given to employing nonlethal weapons that may impair entry and exit to such sites or shut down the bunker's air-conditioning equipment and/or communications, thereby making that site inoperative, but limiting civilian casualties.

If a nuclear penetrating warhead were to be developed for use by the Navy, questions of delivery methods, range, and delivery platform must be considered. The panel believes that the Navy should consider as an option using future SSNs or SSBNs platforms to launch 1,000 km, or greater range, highly accurate ballistic missiles with nuclear warheads that can penetrate and destroy deep bunkered or hardened enemy targets that remain beyond the capability of conventional or nonlethal weapons to destroy or incapacitate.

These shorter-range ballistic missiles could be launched either from a submarine's missile vertical launcher or torpedo tube. Using an active-duty

SSBN in some confined locations such as the Persian Gulf could be operationally risky and could raise serious tensions with other nations in the region. Alternatively, the Navy should consider the feasibility of deploying longer-range SLBMs on an operational SSBN with their nuclear warheads and guidance adapted to achieve high accuracy and deep penetration for use against those critical enemy targets buried deep underground. Another alternative would be to consider using a D-5 missile at sufficiently long ranges and with a sufficiently high ballistic coefficient nose cone to reach impact velocities near Mach 12, with the nose cone weighing in the neighborhood of 5,000 kg and imparting in excess of 30 gigajoules of energy into the impact area—the equivalent of the output of a small nuclear device with an equivalent yield of about 5 tons. The panel recommends that the Navy continue to pursue technology programs that will lead to the deployment of penetrating weapons before 2035, including nuclear penetrating weapons if they are needed.

Shorter-range nuclear penetrating missiles could be deployed on a Navy arsenal ship or arsenal submarine. The deployment of even a few nuclear weapons on arsenal ships or submarines could also cause operational and political problems for the Navy. Nonetheless, it is the panel's opinion that the requirement for a capability to destroy deeply buried and hardened enemy targets will continue to grow over time, and nuclear weapons may be the only feasible way to meet that requirement in the most stressing cases. Weapons appropriate for this task may take more than a decade to develop. The panel also sees a continuing need for the Navy to have a deployed strategic nuclear force well into the next millennium and recommends, therefore, that these nuclear issues receive review and further study by the Department of the Navy.

SUMMARY AND RECOMMENDATIONS

In summary, it is expected that the Navy will continue to maintain a deployed, strategic, nuclear force well into the future and will participate in the modernization and replacement of this strategic force as it approaches its retirement age with due regard to national nuclear policy.

The panel proposes the following recommendations for the Navy:

- Pursue penetrating-weapons technology that consist of either
  - —a high-velocity precision penetrator containing high energy or other conventional lethal mechanisms, or
  - —high-velocity RV-delivered kinetic energy impactors/penetrator or low-yield nuclear warhead penetrators.
- Conduct a study to determine nuclear munition characteristics for optimum target effectiveness to include yield, accuracy versus depth and target hardness in various geological formations, target location error, and weapon-impact velocity needed to destroy targets with no release of radioactivity.

- Consider the use of SSN or SSBN platforms to launch 1,000-km or greater-range, highly accurate ballistic missiles with low-yield (10 tons to 1 kiloton) nuclear warheads that can penetrate and destroy or incapacitate hard and deeply buried enemy targets, functions that are beyond the capability of conventional weapon systems. This may be particularly important against weapons of mass destruction facilities.
- Conduct a comparative study of conventional penetrators, kinetic-energy penetrators, and low-yield, nuclear penetrating munitions.

10

Findings, Conclusions, and Recommendations

The Executive Summary and Chapter 1 provide a reasonably thorough discussion of the results of the panel's attempt to deal with an extremely broad and complex range of issues. This chapter briefly summarizes the panel's findings, conclusions, and the resulting recommendations in each weapon category.

GENERAL CONCLUSIONS

The panel concluded generally that:

- Significant changes in Navy and Marine Corps strategy and weapon mix are needed for the conflicts foreseen for the next 25 to 35 years.
- Increased use of smart weapons can significantly reduce the total cost and logistic requirements of a conflict, while reducing its duration. They can also reduce the vulnerability of launch platforms and munition caches as well as place less stress on dockage.
- If not addressed successfully, surface-ship survivability in the face of enemy TBMs, WMD, cruise missiles, submarines, and mines could be a showstopper in future power-projection operations.
- Aircraft attrition should be minimized by the greatest possible use of standoff weapons in both air-to-air and air-to-surface combat in addition to other factors such as stealth, electronic warfare (EW), and tactics. In general the greater the standoff range, the more costly the weapon. Weapons and weapon delivery system concepts may vary from relatively short-range accurate weapons such as JDAM, delivered by stealth aircraft, to precision weapons launched by

sea-based platforms from significantly great standoff distances. The optimum system design will be a complex function of assumed aircraft costs and attrition rates, the support costs of sea-based aircraft versus arsenal ships, the total number of targets to be destroyed, target detection and designation problems, the cost of weapons as a function of standoff range, and the number of weapons that must be delivered per unit time.

• If aircraft attrition can be eliminated by the use of true stealth aircraft, then short-range, precision-guided, air-to-ground munitions of the JDAM class represent the best means of minimizing ordnance costs in an extended air campaign with many ground targets.

• If there is no prospect that stealth aircraft will be available in adequate numbers, then aircraft attrition is best minimized or avoided by either the extensive use of long-range air-to-surface missiles or the extensive use of sea-launched precision-guided rockets.

• Rocket-powered, precision-guided, long-range (ballistic) weapons launched from surface ships or submarines that are equipped with a variety of warheads and some with terminal guidance could significantly augment the early naval response to an adversary's military actions and satisfy the offshore firepower support requirements of engaged forces ashore.

FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS FOR SPECIFIC WEAPON CATEGORIES

Surface-to-surface Weapons (Also Applicable to Subsurface-to-surface and Air-to-surface Weapons)

Findings and Conclusions

The panel found that currently available technology will permit the development of a family of long-range precision-guided rockets. Specifically, if a family of 5-in.-, 10-in.-, and 21-in.-diameter missiles were to be developed, one 21-in.-, four 10-in.-, or sixteen 5-in.-diameter missiles could be fired from a Mk-41 VLS tube. If the missiles were fired from a surface ship, a major redesign of the Mk-41 VLS would be required to allow double-stacking of 5-in. and 10-in. missiles. On the other hand, if the missiles were emplaced in a submarine-compatible version of a VLS tube and the missiles were ejected by compressed air (as missiles currently are ejected from submarines), no particular problem would be encountered in double- or even (in the case of 5-in.-diameter missiles) triple-stacking the missiles.

The panel's studies also led it to conclude that a significant reduction in the acquisition cost of these missiles could be achieved by the following measures:

• Maximum use of low-cost GPS/INS guidance for attacks on fixed or stationary targets,

- Use of common-stage designs, and
- Large-production runs.

Recommendations

Enhanced ranges are achievable by a tradeoff of warhead weight for accuracy. The panel makes the following recommendations:

- Initiate a development program that can lead to the production of precision-guided rockets with the attributes discussed in Chapter 3 of this report.
- Explore the modifications to the Mk-41 launcher that would be necessary to accommodate the launch of multiple missiles from a single VLS tube.
- Explore the adaptation of Mk-41 VLS tubes in submarines along with the possibilities of using double- or triple-stacked missiles launched by compressed air.

Air-to-surface Weapons

Findings and Conclusions

Since few full-scale air-to-surface weapon developments are under way by the Services, the rate of introduction of new weapons into the inventory over the next 25 to 35 years will be slow. Based on current trends in weapon development, the panel believes that over that period of time, efforts will be made to introduce technologies that will upgrade individual components of the classes of weapons that will remain in service. Many of the changes that the panel suggests in Chapter 3 of this report will, of course, be applicable to the design of future air-to-surface standoff weapons.

The trend toward smart precision standoff and direct-attack munitions will continue. Future air-to-surface inventory will include capability for multiple weapon classes or variants such as antiradiation missiles, unitary weapons for fixed stationary targets, area weapons, and sensor-fused weapons for tactical targets. Direct-attack munitions will be retained and will be delivered by close attack aircraft and lethal UAVs.

Recommendations

The panel recommends the following for the Department of the Navy:

- Pursue technologies for JASSM-class standoff weapons that ensure aircraft survival when targets are attacked at ranges greater than the treaty limit of 600 km for surface-ship-launched ballistic missiles. Present glide-bomb standoff ranges are inadequate to assure aircraft survival when targets defended by SA-12 class systems are attacked.

- Proceed with the present weapon neck-down strategy to reduce the number of weapon types in the Navy inventory.
- Along with other Services, consider the evolution of a long-range standoff weapon that can serve as an effective and affordable submunition transporter.
- Retrofit improved inertial measurement units into the JDAM design so that eventually it can evolve into an affordable direct-attack munition with a 1- to 3-meter circular error of probability.
- Track the Army's TACAWS sensor development and consider applications of these technologies and/or next-generation technologies into future close-support weapons.

Air-to-air Weapons

Findings and Conclusions

For the foreseeable future, missiles will be the weapon of choice for air-to-air engagements. The U.S. advantage of superior pilot training and performance will diminish as fire-and-forget missiles increasingly dominate air combat. Various operational contexts will require a mix of short-, medium-, and long-range air-to-air capabilities, but the emphasis will shift to long-range engagements. Aggressive developments in countermeasures and counter-countermeasures (CCMs) should continue but will always have some degree of fragility against uncertain threat responses.

The panel's specific findings for short-range air-to-air missiles are that weapon time of flight will continue to dominate short-range engagements, often resulting in mutual destruction. The panel believes that current U.S. capabilities are behind the threat, that AIM-9X will regain parity and some advantage over threat missiles, and that enhanced countermeasures are necessary to prevent mutual-destruction engagements. Hard-kill countermeasures (active self-protection) will be necessary to counter close-in aircraft and air-to-air missiles. Solid-state lasers offer the potential to perform this function.

The panel's specific findings for medium-range air-to-air missiles are that AMRAAM and AMRAAM P^3I will provide an advantage for the next decade. Beyond that point, a multimode replacement with an electronically scanned, dual-mode active array and advanced propulsion will be attractive. The panel's specific findings for long-range air-to-air missiles are that networked capabilities can only be fully exploited if a long-range (> 100 nautical miles) air-to-air missile is developed and fielded, that weapon and platform tradeoffs will need to be considered carefully as part of the concept definition of this missile, and that development of this system should begin in the near future to synchronize its fielding with a full airborne CEC capability.

Recommendations

The panel submits the following recommendations in order of priority:

- Initiate a concept definition for a long-range interceptor (> 100 nautical miles) to include weapon and platform tradeoffs as part of a broader air-combat system study.
- As a near-term action, replace AIM-9M as planned.
- Aggressively continue the current evolutionary program of countermeasure and counter-countermeasure development.
- Conduct a technology program to develop key technologies for a laser, active self-protection system.
- Pursue a multimode upgrade or replacement for AMRAAM. Continue the development of dual-mode and superresolution seekers.

Theater Missile Defense

Findings and Conclusions

The panel believes that the Navy's evolutionary TMD strategy, with short-range terminal defense as the first step, is the prudent approach in view of the significant threat uncertainties and the complex technical, operational, and cost issues involved in this new naval mission. However, before the Navy commits to any major development for the next step in the evolutionary process—a long-range pre-apogee intercept system—a thorough evaluation of all reasonable alternatives should be made. The evaluation should include feasibility experiments of critical components and subsystems for the leading alternatives. Serious consideration should be given to long-range TMD interceptor concepts that also have AAW capability in view of the proliferation of advanced antiaircraft weapons and advanced military aircraft that will threaten U.S. control of the air in future littoral conflicts. Because of the defense problems posed by submunitions released from a TBM shortly after it burns out, the Navy needs to undertake a serious evaluation of boost-phase intercept options such as weaponized unmanned air vehicles deployed from Navy platforms.

In view of the growing threat of limited ballistic-missile attack of the U.S. homeland and the potentially important role sea-based defenses might play, the Navy should begin evaluating some strategic defense alternatives in anticipation that the Antiballistic Missile (ABM) Treaty will eventually be changed to allow mobile defenses. The effort should take maximum advantage of BMDO developments and funding and should focus on evolving from the Navy's long-range TMD system.

Recommendations

The panel recommends the following:

- Continue the pusuit of an integrated multilayer TBM defense based on the evolution of Aegis and the standard missile family.
- Explore options for sea-based boost-phase intercept (BPI).
- Vigorously pursue along with other Services a multipronged approach to WMD involving denial, mitigation, and response.

Cruise Missile Defense

Findings and Conclusions

The Navy's newly introduced cooperative engagement capability (CEC), which is a network of monostatic radars, constitutes a revolutionary advance in cruise missile defense (CMD). The panel finds that advances in computational rates, position location accuracy, and broadband data links allow an extension of the CEC concept to the use of a networked multistatic system that should afford major gains in detection ranges based on a simple application of Babinet's principle. The potential for achieving longer missile detection ranges (in nonhorizon limited situations) should be augmented by the introduction of dual-mode capabilities for future variants of the SM-2 and Sea Sparrow missiles. EW technologies have traditionally been effective against both IR- and RF-guided missiles. The panel is persuaded that these techniques should continue to be used as long as they are not negated by CCMs or by the redesign of enemy missile guidance systems. When new CCM techniques are encountered, new EW techniques should be developed. The panel finds that the capabilities of the Navy CIWS system are both mature and impressive, with marginal further improvements likely. The panel was impressed with the new concept in which a highly maneuverable 60-mm-diameter rocket is launched from a gun and guided to the target by a closed semiactive guidance system. In effect, this concept would slow the missile (with a 50-*g* maneuver capability) to the target rather than the gun.

Recommendations

The panel recommends the following:

- Aggressively exploit extensions of the cooperative engagement capability system.
- Introduce dual-mode (RF/IR) guidance for both the Sparrow missile and for future variants of SM-2 missile.
- Explore the FireBox concept (discussed in Chapter 5), and if initial tests

appear favorable, consider initiating its development as a future replacement for the close-in weapon system.

Laser Weapons

Findings and Conclusions

Laser weapons currently under development by the Army (THEL for battlefield air defense), Air Force (ABL for boost-phase intercept), and BMDO (SBL also for boost-phase intercept) may, if they are successful, provide critical combat support for Marine Corps ground warfare and for Navy and Marine Corps landing operations. These weapons address threats that currently cannot be addressed in any other way.

Future developments in laser technology offer the promise of more compact (DPSSL in the nearer term, CHPDA in the longer term) or more effective (FEL in the mid-term) weapons. DPSSL- and CHPDA-based weapons could provide the Marine Corps with a superior version of a battlefield air defense weapon, the Navy and the Marine Corps with an aircraft self-defense weapon, and the Navy with a viable escort defense ASMD weapon to protect logistics vessels during inshore operations. FEL-based weapons could provide the Navy with a robust self-defense ASMD weapon, particularly, but not narrowly, on future electric-drive vessels. The Navy already has an expressed interest and active role in the FEL technology, but not in the DPSSL or CHPDA technologies, which are being evaluated by the Army and the Air Force, respectively.

Recommendation

The panel recommends that the Navy and the Marine Corps evaluate the impact of the above development programs (THEL, ABL, SBL) and compact weapon technologies (DPSSL, CHPDA, FEL) on their own combat requirements and, as appropriate, support and participate in the Army and Air Force development.

Undersea Weapons

Findings and Conclusions

Technology permits development of weapons optimized for offensive and defensive operations in littoral regions. These include the following:

- Concepts for guidance and control of the future that will be enabled by technology to provide communication, networking, and interoperability among weapons and platforms of all classes; and intelligent control, selective targeting, and IFF for all weapons, along with improved performance against quiet targets

and discrimination against countermeasures in acoustically challenging environments using wide-bandwidth signals.

- Energy systems of the future that will strive to produce higher energy densities than are currently achievable. The impact of these achievements will be environmentally sustainable, long-endurance energy systems that can support multimission UUV capability.
- Propulsion technology growth that will be a major influence on the future direction of undersea weapon capabilities, as it is one of the major building blocks of an undersea weapon. This will result in the emergence of safe, environmentally friendly power sources having higher energy and power densities and lower life-cycle costs, and weapons with compact, quiet, high-performance turbines and other thermal engines.

Warhead science and technology developments that are expected to have a major impact on the weaponry capabilities of the naval forces in the 2035 time frame are summarized as follows:

- Small cost-effective undersea weapons of all types, capitalizing on MEMS fuse technology and more energetic explosives;
- Improved weapon system safety by insensitive munition compliance;
- Robust lightweight torpedo warheads (12-in. diameter) capable of rupturing the hull of the projected robustly constructed submarine threat;
- Half-length heavyweight torpedoes with small, explosive warheads capable of rupturing the hull of the projected submarine threat while significantly increasing the loadout of torpedoes on U.S. submarines;
- Small effective sea mines with significantly increased lethal radius against surface ships and submarines, and reduced delivery requirements compared with those of the current Quickstrike mines; and
- Reduced weight and weight of explosive systems to counter enemy sea mines, surf zone, and beach mines.

The panel is persuaded of the feasibility of the development of a torpedo counterweapon that will rely on commonality of technology with the other thrusts listed above. It will result in a hard-kill torpedo defense capability that will enhance surface and subsurface ship defense by providing point-defense against hostile torpedo attacks from submarines.

Recommendations

The panel recommends that the following enabling technologies be pursued, leading to a torpedo defense capability through an antitorpedo torpedo and or rapid-response hypervelocity weapon, an undersea CEC based on broadband networked sensors and improved processing, and improved shallow-water sensor and guidance capabilities:

- Broadband sensor and signal-processing technology that provides increased capability in difficult littoral environments and aggressive countermeasure scenarios;
- Propulsion alternatives to OTTO-fuel that provide performance gain and reduced life-cycle support costs;
- High-energy-density technology for low-power autonomous weapons and long-endurance UUV applications;
- Cooperative engagement concepts;
- High-power-density propulsion technology for high-speed weapons and smaller torpedos with equivalent or better capability;
- More energetic explosives and increased warhead performance exploiting new materials and novel damage mechanisms; and
- Torpedo-defense concepts based on quick-reaction or intercept weapons designed to attack torpedoes.

Special-purpose Devices and Techniques

Information Warfare

Findings and Conclusions

Offensive information warfare can, if implemented effectively, have highly leveraged effects on the outcome of confrontations. The Navy is a player in this world, and the panel has every confidence that for the foreseeable future it can and will continue to be an effective practitioner of offensive IW.

Recommendations

Because the techniques of IW are, and will continue to be, in a state of evolution, the panel cannot recommend programmatic directions for investment. These directions will be, and must continue to be, responsive to future evolutions of the technology of data storage, protection, and transmission.

The panel thus suggests the following:

- Efforts should be made to make operational naval commanders fully aware of the military implications of the techniques of offensive IW.
- A general realization should be established throughout the U.S. naval forces that the techniques of offensive IW are symmetrical. If there are specific vulnerabilities in U.S. systems, our adversaries can exploit them with disastrous consequences. Defensive IW capabilities may become as important to the U.S. Navy as CMD or TMD.
- Success in offensive IW will correlate with past investment in both people and in the development of techniques. People must be trained to understand the

perplexities of the field. In effect, IW must be recognized as a naval career specialty. The funding priorities for the development and procurement of IW weapons must be considered to be coequal with the funding priorities for other weapon systems.

Incapacitating Weapons and Techniques

Findings and Conclusions

All evidence available to the panel indicates that during the next 25 to 35 years, incapacitating (less-than-lethal) weapons and techniques will play an increasingly important role. Although their importance in a conflict with a major peer competitor or in a major regional contingency might be restricted, their importance in OOTW or in hostage standoff situations will be significant.

Naval forces who are assigned to execute risky OOTW plans or to recover hostages are often faced with dreadful choices between executing an effective self-defense and causing needless civilian casualties. Such casualties are counterproductive to the best interests of the United States. Although few people will contest the right of self-defense, the death of innocent civilians is to be avoided on humanitarian grounds and can be expected to be recorded on ubiquitous television cameras and very rapidly turned into a rallying point for a U.S. adversary.

In addition to the projected use of incapacitating weapons in hostage situations and in opposed OOTW situations, naval forces need to have improved techniques available that allow them to stop and divert ships without sinking them and to force aircraft to land without shooting them down.

Recommendations

From the standpoint of weapon maturity and operational concepts for their use, the techniques discussed in this section are in their infancy. The panel believes that U.S. naval forces should do the following:

- Concentrate on the development of tactics and doctrine for the use of incapacitating weapons.
- Develop tactics and techniques for forcing aircraft to land and ships to divert as U.S. forces direct them.
- Continue the development of incapacitating weapons that are more effective, reliable, and politically acceptable than are current devices.
- Recognize that public release of the specific technologies to be employed will allow countermeasures against U.S. forces or interests.

Weapons and Techniques for Urban Warfare

Findings and Conclusions

In general, the panel believes that the first principle of urban warfare should be to avoid it, if at all possible. For those situations where urban conflict cannot be avoided, the panel believes that the capabilities to use improved robotic sensors, lethal mini-UAVs, concrete-breaching and tunneling devices, and robotic emplacement of explosives at structural members should improve significantly the future capabilities of naval forces to undertake and win battles in urban areas. Utilization of nonlethal weapons may have an important role in urban warfare.

Recommendations

The panel makes the following suggestions:

- Sensors and PMMs should be developed that allow accurate and efficient target designations in urban areas and risk-free remote placement of explosives or nonlethal weapons.
- Naval forces likely to engage in urban combat should develop improved tactics and doctrine based on improved sensors, lethal miniature UAVs, and PMMs.

New Techniques for Infrastructure Attack

Findings and Conclusions

The panel is persuaded that well-conceived and rapidly executed attacks on an adversary's infrastructure will have a substantial impact on an adversary's willingness to terminate a conflict on terms that are acceptable to the United States.

Below are listed the military capabilities, weapons, and techniques that are needed:

- Identify and target with precision the critical nodes and links in the adversary's civil structure.
- Deliver weapons accurately or execute specific techniques that destroy only the target of interest and importance.
- Isolate the adversary's military forces from support of the civil sector of society.
- Achieve total information dominance.
- Effectively attack the will of the adversary's populace and leadership to continue a conflict.

The capabilities summarized here will be used as appropriate by theater CINCs to achieve conflict resolution as rapidly as is feasible. The weapons and techniques discussed in Chapter 8 certainly are not and will not be unique to naval forces. However, to provide future CINCs with the tools necessary for effective infrastructure attack, naval forces must be equipped with the necessary tools and techniques and be trained in their use.

Recommendations

The panel suggests that U.S. naval forces do the following:

- Develop a cadre of personnel who are knowledgeable in the principles of infrastructure attack and who understand the tools needed for such attacks.
- Be equipped with precision weapons and appropriate warheads needed to destroy critical nodes and links in infrastructure networks.
- Be trained and equipped to take such actions as will assure immediate information dominance whenever required.
- Establish robust connectivity with National systems and organizations that identify the specific critical nodes that must be attacked.

Nuclear Weapons

Findings and Conclusions

Based on its review of the problem of negating hard-to-defeat targets that store weapons of mass destruction, the panel believes that special-purpose weapons will ultimately be required for the negation of deeply buried hardened targets (e.g., WMD repositories). Doctrines and options for attack on hard-to-destroy targets are required. Options include conventional attack on externalities (air intakes, exits, communications, and power sources), large multigigajoule kinetic-energy earth penetrators, and earth-penetrating weapons with a small nuclear warhead. Of the available options for dealing with hard, deep targets, nuclear weapons (although politically unattractive) are the best alternative.

Recommendations

To provide the best ensemble of options to national leadership, the panel offers the Navy the following recommendations:

- Develop and understand the limitations of penetrating weapons:
  - A high-velocity precision penetrator containing HE or other conventional lethal mechanisms;

— High-velocity reentry vehicle (RV)-delivered kinetic-energy impactors/penetrators and nuclear warhead penetrators.

- Conduct a study to determine nuclear munition characteristics for optimum target effectiveness to include yield, accuracy versus depth and target hardness in various geological formations, TLE, and weapon impact velocity needed to destroy targets with no release of radioactivity.

PRIMARY RECOMMENDATIONS—INITIATIVES FOR WEAPONS AND SPECIAL TECHNIQUES

Accordingly, the panel recommends the following new Department of the Navy initiatives:

- *Surface-to-surface (also applicable to subsurface-to-surface and air-to-surface):* a family of low-cost, high-volume, long-range precision ballistic weapons; and
- *Air-to-air:* a new weapon to support a long-range engagement capability that exploits airborne cooperative engagement capabilities (CECs).

The panel also recommends continued Department of the Navy emphasis on the following:

- *Air-to-surface:* continue the trend toward smart precision standoff and direct-attack munitions.
- *Cruise missile defense/antiballistic missile (CMD/ABM):* continue the pursuit of an integrated, all-platform, multilayer defense with a variety of weapons.
- *Undersea warfare:* weapons optimized for offensive and defensive operations in littoral regions.
- *Offensive/defensive mine warfare:* mines operated by networked sensor systems.
- *Special techniques:* emphasize special lethal and less-than-lethal warfare techniques as well as an integrated WMD defense.

APPENDIXES

A

Terms of Reference

CHIEF OF NAVAL OPERATIONS

28 November 1995

Dear Dr. Alberts,

In 1986, at the request of this office, the Academy's Naval Studies Board undertook a study entitled "Implications of Advancing Technology for Naval Warfare in the Twenty-First Century." The Navy-21 report, as it came to be called, projected the impact of evolving technologies on naval warfare out to the year 2035, and has been of significant value to naval planning over the intervening years. However, as was generally agreed at the time, the Navy and Marine Corps would derive maximum benefit from a periodic comprehensive review of the implications of advancing technology on future Navy and Marine Corps capabilities. In other words, at intervals of about ten years, the findings should be adjusted for unanticipated changes in technology, naval strategy, or national security requirements. In view of the momentous changes that have since taken place, particularly with national security requirements in the aftermath of the Cold War, I request that the Naval Studies Board immediately undertake a major review and revision of the earlier Navy-21 findings.

The attached Terms of Reference, developed in consultation between my staff and the Chairman and Director of the Naval Studies Board, indicate those topics which I believe should receive special attention. If you agree to accept this request, I would appreciate the results of the effort in 18 months.

Sincerely,

J. M. BOORDA
Admiral, U.S. Navy

Dr. Bruce M. Alberts
President
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Enclosure

TERMS OF REFERENCE

TECHNOLOGY FOR THE FUTURE NAVY

The Navy-21 study (Implications of Advancing Technology for Naval Warfare in the Twenty-First Century), initiated in 1986 and published in 1988, projected the impact of technology on the form and capability of the Navy to the year 2035. In view of the fundamental national and international changes -- especially the Cold War's end -- that have occurred since 1988, it is timely to conduct a comprehensive review of the Navy-21 findings, and recast them, where needed, to reflect known and anticipated changes in the threat, naval missions, force levels, budget, manpower, as well as present or anticipated technical developments capable of providing cost effective leverage in an austere environment. Drawing upon its subsequent studies where appropriate, including the subpanel review in 1992 of the prior Navy-21 study, the Naval Studies Board is requested to undertake immediately a comprehensive review and update of its 1988 findings. In addition to identifying present and emerging technologies that relate to the full breadth of Navy and Marine Corps mission capabilities, specific attention also will be directed to reviewing and projecting developments and needs related to the following: (1) information warfare, electronic warfare, and the use of surveillance assets; (2) mine warfare and submarine warfare; (3) Navy and Marine Corps weaponry in the context of effectiveness on target; (4) issues in caring for and maximizing effectiveness of Navy and Marine Corps human resources. Specific attention should be directed, but not confined to, the following issues:

1. Recognizing the need to obtain maximum leverage from Navy and Marine Corps capital assets within existing and planned budgets, the review should place emphasis on surveying present and emerging technical opportunities to advance Navy and Marine Corps capabilities within these constraints. The review should include key military and civilian technologies that can affect Navy and Marine Corps future operations. This technical assessment should evaluate which science and technology research must be maintained in naval research laboratories as core requirements versus what research commercial industry can be relied upon to develop.

2. Information warfare, electronic warfare and the exploitation of surveillance assets, both through military and commercial developments, should receive special attention in the

review. The efforts should concentrate on information warfare, especially defensive measures that affordably provide the best capability.

3. Mine warfare and submarine warfare are two serious threats to future naval missions that can be anticipated with confidence, and should be treated accordingly in the review. This should include both new considerations, such as increased emphasis on shallow water operations, and current and future problems resident in projected worldwide undersea capability.

4. Technologies that may advance cruise and tactical ballistic missile defense and offensive capabilities beyond current system approaches should be examined. Counters to conventional, bacteriological, chemical and nuclear warheads should receive special attention.

5. The full range of Navy and Marine Corps weaponry should be reviewed in the light of new technologies to generate new and improved capabilities (for example, improved targeting and target recognition).

6. Navy and Marine Corps platforms, including propulsion systems, should be evaluated for suitability to future missions and operating environments. For example, compliance with environmental issues is becoming increasingly expensive for the naval service and affects operations. The review should take known issues into account, and anticipate those likely to affect the Navy and Marine Corps in the future.

7. In the future, Navy and Marine Corps personnel may be called upon to serve in non-traditional environments, and face new types of threats. Application of new technologies to the Navy's medical and health care delivery systems should be assessed with these factors, as well as joint and coalition operations, reduced force and manpower levels, and the adequacy of specialized training in mind.

8. Efficient and effective use of personnel will be of critical importance. The impact of new technologies on personnel issues, such as education and training, recruitment, retention and motivation, and the efficient marriage of personnel and machines should be addressed in the review. A review of past practices in education and training would provide a useful adjunct.

9. Housing, barracks, MWR facilities, commissaries, child care, etc. are all part of the Quality of Life (QOL) of naval personnel. The study should evaluate how technology can be used to enhance QOL and should define militarily meaningful measures of effectiveness (for example, the impact on Navy readiness).

10. The naval service is increasingly dependent upon modeling and simulation. The study should review the overall architecture of models and simulation in the DoD (DoN, JCS, and OSD), the ability of models to represent real world situations, and their merits as tools upon which to make technical and force composition decisions.

The study should take 18 months and produce a single-volume overview report supported by task group reports (published either separately or as a single volume). Task group reports should be published as soon as completed to facilitate incorporation into the DoN planning and programming process. An overview briefing also should be produced that summarizes the contents of the overview report, including the major findings, conclusions, and recommendations.

B

U.S. Arms Control Treaties

With the advent of the Cold War and subsequent buildup of conventional and nuclear arms in the post-World War II era, the United States negotiated and entered into numerous multilateral and bilateral arms control agreements that may have an impact, if they remain in force, on the nature and use of U.S. military weapons in the future. Of special importance to the Navy are those treaties that limit or ban offensive and defensive strategic systems, including the Strategic Arms Limitations Treaty (SALT) I and Antiballistic Missile (ABM) Treaty, and the Strategic Arms Reduction Treaty (START) I and II. SALT I has been overtaken by START I, and the ABM Treaty is of limited duration.

Other agreements such as the Intermediate Nuclear Force (INF) Treaty, which pertains to U.S. and Russian ground-launched cruise and ballistic missiles, the Conventional Forces Europe Treaty limiting conventional ground forces in Europe, the Biological and Chemical Weapons Conventions along with the Geneva Protocol of 1925 banning such weapons, and possibly the Environmental Modification Convention of 1977 prohibiting the hostile use of environmental modification techniques may also influence the direction of development that Navy and Marine Corps weapons take. A significant number of international laws on armed conflict can also influence the development and use of Navy and Marine Corps weapons, but primarily weapons that may be used by Marine Corps forces on land. A summary of the more important elements of the strategic arms reductions treaties is given below as reported in the unclassified literature.

The primary issues between the United States and Russia regarding the ABM Treaty relate to Article V.1, in which each side agrees not to develop, test, or deploy ABM systems or components that are sea-based, air-based, space-based,

or mobile land-based and to Article VI, in which each side agrees not to give missiles, launchers, or radars (other than ABM interceptor missiles, launchers, and radars) capabilities to counter strategic ballistic missiles or their elements in flight trajectory and not to test such missiles in an ABM mode. A major question is what is permissible to develop for theater missile defenses, and this issue has been under negotiation between the United States and Russia for several years. The most contentious issue has been the reaching of an agreement by both sides on an acceptable upper-bound for TMD interceptors' range and velocity. Also of concern for future U.S. TBM developments is Treaty Article II, which defines ABM radars and interceptors as those that have been tested against strategic ballistic missiles. Strategic ballistic missiles are defined in SALT I as having a range greater than the shortest distance between the northeastern border of the United States and the northwestern border of the former Soviet Union, about 5,500 km.

The START I ratified by the U.S. Congress limits the number of total strategic warheads for the United States and Russia (former Soviet Union) to 6,000, including those on ICBMs, SLBMs, and bombers (Art. II. 1.b), with the total number of ICBM and SLBM warheads limited to 4,900 (Art. II.b.i) and the number of ICBM warheads to 1,100 (Art. Ll.b.ii). Article V.2.b. prohibits the deployment of "heavy" SLBMs. A heavy SLBM is defined in Treaty Definition 40 as having a launch weight greater than 106,000 kg, or a throw weight greater than 4,350 kg. The treaty bans installation of SLBM launchers on submarines not originally constructed as ballistic missile submarines (Art. V. 17), and bans the deployment of ballistic missiles on surface ships with ranges greater than 600 km (Art. V. 18), but does not ban the deployment of ballistic missiles on submarines. Definition 109 of the treaty defines an SLBM as a submarine-launched ballistic missile with a range greater than 600 km, and thus all ballistic missiles on submarines, including those with conventional HE warheads, with ranges greater than 600 km may be countable under the current treaty language as being within the SLBM treaty limits. In an agreed declaration on July 31, 1991, the United States stated that nuclear SLCMs with less than 600-km range will not be declared under START I, nonnuclear SLCMs will not be declared at all, and the number of declared nuclear SLCMs with ranges of greater than 600 km will not exceed 880 in any one year. Further, since ratification of START, new understandings may have been introduced and agreed to that could affect counting rules, verification procedures, and the like that are not noted here.

START II has not yet been ratified by the Russian Duma, but when signed by the United States and Russia will reduce the number of strategic warheads of each side to between 3,000 and 3,500 (Art. 1.3). Each side will be allowed no more than 1,750 warheads on SLBMs (Art. I.4a), and a ban on the deployment of MIRVed ICBMs (Art. 1.4b) and heavy ICBMs (Art. I.4c), but not MIRVed SLBMs. The implementation of START II is to be completed by no later than January 1, 2003 (Art. 1.3) and remain in force so long as START I remains in force.

It should be noted that there are often varying interpretations of treaty language. On occasion, particularly in bilateral treaties with Russia, one or the other side will add an interpretation of the treaty that is either meant to clarify or to allow a side to develop or deploy weapon systems not meant to be controlled by existing treaties. Consultative commissions have been established whereby disagreements and proposed treaty language changes are negotiated. There are also precedents set in past treaties that can influence how new interpretations may be made to allow new nonnuclear weapons systems in the future. Thus START I has developed elaborate rules and verification procedures allowing the United States to convert former B-52 aircraft from nuclear bombers to conventional ones.

As noted above, START II has not been ratified by the Russian Duma, and the United States has failed to ratify the Chemical Weapons Convention. Although the treaty is clear that a ballistic missile launched from a submarine *is* defined as an SLBM if it has a range greater than 600 km, it is uncertain whether an exception may be made on the basis that there are discernible differences between 22-in. VLS launchers on an arsenal submarine and an 84-in. D-5 launcher on a Trident submarine, as was done in START I for the conversion of U.S. and Russian bombers from carriers of nuclear weapons to carriers of conventional weapons only.

The United States has imposed a moratorium on all nuclear weapon testing until a Comprehensive Test Ban Treaty (CTBT) is in force. In September 1996, the United Nations Commission on Disarmament completed a multilateral negotiated CTBT that as of February 1997 had 40 of the 44 signatories needed for it to take force. The CTBT has been signed by the United States and will be submitted to the Congress by the administration for ratification, where its acceptance is uncertain, at least in its current form. Only the governments of India and, thereby, Pakistan have indicated an unwillingness to sign. Iran has signed but reserved its right to pursue research into nuclear matters.

C

The Changing Face of 21st-Century Naval Forces

Gazing into crystal balls is dangerous for amateurs and professionals alike. It is also a necessary exercise, especially for naval force planners. The long amortization time of naval weapon systems requires that one look well into the first third of the 21st century so that good research and procurement decisions can be made soon if a different naval force is to be ready for new challenges.

In its role as the world's only true superpower, the United States has certain fundamental interests, which are not likely to change over the decades. We are a maritime trading nation supportive of open sea-lanes and free market economies. Any regional despot or emerging peer competitor with contrary ideas becomes a threat to the peace and prosperity of the United States and our trading partners.

Ninety-nine percent of the time we will fulfill our vital naval mission of forward presence. Major combatant ships and their crews of sailors and marines are a strong visual assurance with immeasurable impact on our friends and enemies alike that the world's premiere trader is committed to and interested in international events. During these times of relative peace, noncombatant evacuation operations of U.S. and third-party citizens from areas of unrest and turmoil will be frequent and demanding. Humanitarian aid in case of natural disaster or religious or ethnic strife will also put demands on forward-deployed forces. In the above instances, less-than-lethal weapons, transportation, medical, and logistics capabilities will be the dominant requirements. Unfortunately, though, unless naval forces are overwhelmingly engaged in noncombat operations (as a function of time), forces, weapons, and equipment cannot be sized or justified for this mission. It comes as an additional duty for forces designed for naval combat power projection on the world's littorals.

The "evil empire," our reliable threat for 45 years, evolved as a mirror image of us. Large surface-action combatants, submarines, aircraft, missiles, tanks, and artillery were all familiar systems to defend against. Our Gulf War performance proved we excelled in our preparation for handling the conventional threat. All of our potential adversaries also learned a great deal from the Gulf War. Thus, there has been an emergence around the world of the asymmetrical threat. In order to inhibit the United States from projecting naval power on to the littorals, the world's pariahs are steadily preparing an asymmetrical challenge for which we are ill prepared.

Because of limitations and shortfalls in our force projection package today, Navy combatants are forced into the near-shore brown water where our primary sensors are environmentally disadvantaged. In addition, a new shore-based threat array presents itself, much of which can be visually targeted. The most worrisome new threats include land- or small craft-launched antiship cruise missiles (ASMs), tactical ballistic missiles (TBMs) potentially with WMD warheads, shallow-water and very-shallow-water anti-invasion mines, and the diesel submarine.

The first response by the naval services was to get all the major combat ships over the horizon. By replacing the amphibious assault vehicle (AAV) with the advanced amphibious assault vehicle (AAAV), all of the task force shipping can now remain at least 30 miles at sea. This is a major improvement for the fleet in several ways—radars and sonars are back where they were designed to work; battle space is increased and reaction time is relaxed; visual targeting by the enemy is no longer possible; assault ships do not have to cruise around in near-shore mine fields; the enemy will have to invest in over-the-horizon (OTH) targeting equipment; and diesel submarines chasing 15- to 20-knot surface ships are easy prey for nuclear attack submarines escorting the fleet units. There is much value in the AAAV program in the near term and it should be accelerated. The V-22 will do for the high-value amphibious assault ship, multipurpose (LHD) amphibious assault ship, and general-purpose (LHA) platforms what AAAV will do for landing ship dock (LSD) and amphibious transport dock (LPD) assets. The big-deck amphibians will be able to operate 150 to 200 nautical miles offshore, rather than 50 nautical miles, and will be virtually under the wing of the carrier battlegroup for protection.

Although extending the battle space with V-22 and AAAV helps the task force deal with a number of threats, the assault force as we know it today with fixed support facilities (airfields, fuel dumps, ammunition storage, and logistics facilities) is a high-risk operation until the TBM/WMD threat is greatly reduced or eliminated. Ultimately the naval force projection team would like to remain sea based and mobile. Today, that is not possible because of one major shortfall. There is currently no naval surface fire support with ranges and payloads that permit firepower to come from OTH to targets 100 to 200 nautical miles inland in a few minutes. This requires the landing force to bring its own organic fire support ashore. About 70 percent of the ship-to-shore assault lift is used to

support the firepower part of the combat equation. One LCAC brings one tank (a very low flying slow C-5A or C-17) or two towed 155-MM artillery pieces with their prime movers. A Marine Corps division's tank battalion and artillery regiment do not arrive from OTH for a number of hours. Then comes resupply of fuel, ammunition, and spares. Clearly, the key to sea-based logistics becoming a reality is naval surface fire support (NSFS) becoming a reliable, day-and-night, all-weather part of the naval power projection equation.

Just minutes prior to the transition period for surface assault, stealth Air Force air and NSFS ballistic and cruise missiles must have beaten down air defense systems except for those undetectable man-portable low-altitude variants in the hands of enemy infantry. All fixed-wing assets that can reach the objective area now must take control of the local air space while V-22 crews insert widely dispersed infantry teams. We have now reached another limiting factor on the critical path during the transition period. All of the assault shipping in the U.S. Navy can lift only about 20,000 marines—one thin Marine Expeditionary Force (MEF). During this period while we are learning sea-basing and deep penetration, the bulk of land-based combat power comes through the maritime prepositioned force (MPF) and the follow-on Army MPF.

The MPF forces are potent when assembled for combat. However, they need at least one large airfield, a port with many deep-water piers, and about 10 days to get ready for combat. Securing an airfield and port could well involve urban combat by the assault forces early on. Ports and airfields are seldom found without cities attached. Even after the airfield and port facilities are secured, heavy risk attends the lengthy preparation phase during which those facilities are employed in bringing in the MPF forces. In this phase there will be high-value concentrations of personnel and materiel that will be ideal targets for attack by TBMs, particularly TBMs carrying WMD payloads. It is not likely that the preparation phase can be succesfully completed unless the threat of TBM attack is reduced.

WAR IN THE URBAN CANYONS AND GULLIES

Historically, fighting in and through villages, towns, and cities has produced three results: (1) large numbers of infantry casualties, (2) heavy structural damage from heavy weapons, and (3) many civilians killed or wounded when they chose to stay in the combat zone.

Seventy percent of the world's populations live within 50 miles of the sea. Trouble tends to happen where there are large concentrations of people. Therefore, if dealing with chaos in the littorals is assumed important for the 21st century, naval forces will have to "fight smart" in urban terrain.

A number of ideas and some promising technologies should be melded and tested. The urban battles of the 21st century will most likely not be against large, organized, traditional armies. Armies do not like to fight in cities. The U.S.

naval forces engagements in cities are more likely to be short with very specific missions that do not require the taking and running of a city. This is true primarily because taking and running a large city is too hard. The 21st-century urban combat is more likely to take on the overall nature of intense intelligence gathering with short, sharp periods of concentrated violence.

The new technologies that make these visions possible have matured in the last decade or are now appearing on laboratory shipping docks. First, a major advantage to the attacker now is vertical takeoff and landing (VTOL). The speed, survivability, and navigation systems of modern VTOL craft such as the V-22 will allow large military formations to remain safely at sea and to appear only in the right place and right time to consummate the action. Second, UAV technology ranging from large, long-endurance platforms to microminiature expendables will enable the attacker to rapidly establish a clearer picture of the urban canyons, gullies, and caves than ever before possible. The challenge is the systems engineering of these technologies to produce a zoom capability to isolate trouble-making forces and leadership, which can make them vulnerable to precision force application. Third, the development of robotic aids for direct assault teams is a new and promising area that begs to be developed and tested. Mobile unattended ground sensors and leave-behind sentinels will be large force multipliers in modern combat.

Robotic combat engineers and sniper detectors will save the lives of many squad pointmen and assault teams crossing the street to make the first entry into a defended building. Finally, a whole family of less-than-lethal systems must be explored and proven. Since much of the future urban combat will not involve total destruction of the environment, most of the civilian populace may not leave the area of interest. In many cases, they may be hostile to U.S. naval forces even if not armed or violent. Suppressing them and the few bad actors they may hide will be a less-than-lethal requirement. Excessive force on the evening news is a nonstarter for future joint task force commanders.

D

Acronyms and Abbreviations

AA	Air-to-air
AAAV	Advanced amphibious assault vehicle
AAAV(R)	Advanced amphibious assault vehicle (robotic)
AAM	Air-to-air missile
AAV	Amphibious assault vehicle
AAW	Antiair warfare
ABL	Airborne-based laser
ABM	Antiballistic missile
A/C	Aircraft
A/D	Analog-to-digital
ADCAP	Advanced capability
ADN	Ammonium dinitramide
AEW	Airborne early warning
AIM	Airborne intercept missile
AJ	Antijam
ALGW	Advanced lightweight ground weapon
AlH_3	Aluminum hydride
ALL	Airborne Laser Laboratory
AMRAAM	Advanced medium-range air-to-air missile
AOA	Angle of attack
A_p	Presented area
AP	Ammonium perchlorate
APC	Armored personnel carrier
APT	Acquisition pointing and tracking

ARG	Amphibious ready group
ASAD	Advanced system for air defense
ASARG	Advanced Synthetic Aperture Radar Guidance
ASARS	Advanced Synthetic Aperture Radar System
ASM	Antiship missile
ASMD	Antiship missile defense
ASUW	Antisurface warfare
ASW	Antisubmarine warfare
ATACMS	Advanced Tactical Missile System
ATO	Air tasking order
ATR	Automatic target recognition
ATT	Antitorpedo torpedo
AUV	Autonomous unmanned vehicle
AWACS	Airborne warning and control system
AWW	Above-water warfare
BASS	Bulk avalanche semiconductor switch
BAT	Brilliant antitank (weapon)
BDA	Battle (or bomb) damage assessment
BDI	Battle (or bomb) damage indicator
BGPHES	Battle-group passive horizon extension system
BLGM	Ballistic laser-guided munition
BM(A)	Battle manager, afloat
BMD	Ballistic missile defense
BMDO	Ballistic Missile Defense Organization
BPI	Boost-phase intercept
BVR	Beyond visual range
C^3I	Command, control, communications, and intelligence
C^4I	Command, control, communications, computing, and intelligence
C^4I/RSTA	Command, control, communications, computing, intelligence/ reconnaissance, surveillance, and target acquisition
CAP	Combat air patrol
CAPTOR	Encapsulated torpedo
CBW	Chemical and biological warfare
CCD	Camouflage, concealment, and deception
CCM	Counter-countermeasure
CEC	Cooperative engagement capability
CEP	Circular error of probability
CFE	Conventional Forces Europe
CHPDA	Coherent high-power diode array
CID	Combat identification
CINC	Commander-in-chief
CIWS	Close-in weapon system

CL-20	Hexanitrohexaazaisowurtzitane
CLO	Counter low observable
CM	Cruise missile
CMD	Cruise missile defense
CNA	Center for Naval Analyses
CNO	Chief of Naval Operations
COEA	Cost and operational effectiveness analysis
COIL	Chemical oxygen iodine laser
CONOPS	Concept of operations
COTS	Commercial off the shelf
CPA	Closest point of approach
CPIA	Chemical Propulsion Information Agency
CTBT	Comprehensive Test Ban Treaty
CVBG	Carrier battle group
CVN	Nuclear-powered aircraft carrier
CW/BW	Chemical warfare and biological warfare
D^4E	Deny, deceive, disrupt, destroy, and/or exploit
DAM	Direct-attack munition
DARPA	Defense Advanced Research Projects Agency
DEW	Directed-energy weapon
DF	Deuterium fluoride
DIPCM	Distributed personnel interdiction cluster munitions (Mk-77 grenade) submunition
DMBT	Dimethylbitetrazole
DOD	Department of Defense
DOE	Department of Energy
DOS	Deformable ordnance system
DPICM	Dual-purpose improved conventional munition
DPSSL	Diode-pumped solid-state laser
DSB	Defense Science Board
DSMAC	Digital scene matching area correlation
DSP	Defense support program
DTRM	Dual-thrust rocket motor
EC	Electronic combat
ECM	Electronic countermeasure
EFP	Explosively formed projectile
EKV	Exoatmospheric kinetic vehicle
ELINT	Electronic intelligence
EM	Electromagnetic
EMCON	Emission control
EML	Electromagnetic launcher
EMP	Electromagnetic pulse
EO	Electro-optical

ER-FOG-M	Extended-range fiber-optic guided missile
ERGM	Extended-range guided missile
ERP	Effective radiated power
ESM	Electronic support measure
ESSM	Evolved Sea Sparrow missile
ET	Electrothermal
ETC	Electrothermal chemical
EW	Electronic warfare
FEL	Free-electron laser
FLIR	Forward-looking infrared
FM	Frequency modulation
FOB	Forward operations base
FOG-M	Fiber-optic guided missile
FOV	Field of view
FSCL	Fire support coordination line
G&C	Guidance and control
GAP	Glycidylazide polymer
GDL	Gas dynamic laser
GGP	GPS guidance package
GLONASS	Global Navigation Satellite System
GP	General purpose
GPS	Global Positioning System
HADN	Hydroxylammonium dinitramide
HALE	High-altitude long-endurance
HANF	Hydroxylammonium nitroformate
HARM	High-speed antiradiation missile
HBE	High-bubble energy
HE	High energy
HEDM	High-energy density materials
HELSTF	High-energy Laser Test Facility
HES	High-explosive system
HF	Hydrogen fluoride
HGV	Hypersonic glide vehicle
HMX	Cyclotetramethylenetetranitramine
HNF	Hydrazinium nitroformate
HNFX	3,3,7,7-tetrakis(difluoramino)octahydro-1,5-dinitro-1,5-diazocine
HPM	High-power microwave
HTA	High-temperature accelerant
HUMINT	Human intelligence
ICBM	Intercontinental ballistic missile
IFF	Identification, friend or foe
IHPRPT	Integrated High Payoff Rocket Propulsion Technology

IIR	Imaging infrared
IMU	Inertial Measurement Unit
INF	Intermediate Nuclear Force
INS	Inertial Navigation System
InSb	Indium antimonide
IOC	Initial operational capability
IR	Infrared
IRCM	IR countermeasure
IRST	Infrared search and track
ISAR	Inverse synthetic aperture radar
I_{SP}	Specific impulse
IW	Information warfare
JANNAF	Joint Army, Navy, NASA, Air Force Interagency Propulsion Committee
JASSM	Joint air-to-surface standoff missile
JDAM	Joint direct-attack munition
JFACC	Joint forces air component commander
JFLCC	Joint forces land component commander
JMCIS	Joint Maritime Command Information System
J/S	Jam to signal
JSOW	Joint standoff weapon
JSTARS	Joint Surveillance and Target Attack Radar System
JTIDS	Joint Tactical Information Distribution System
KKV	Kinetic-kill vehicle
LAV	Light-armored vehicle
LCAC	Landing craft, air cushioned
LDRJ	Low-drag ramjet
LEAP	Lightweight exoatmospheric projectile
LEO	Low Earth orbit (satellite)
LGB	Laser-guided bomb
LGM	Laser-guided munition
LHA	Amphibious assault ship (general purpose)
LHD	Amphibious assault ship (multipurpose)
LHT	Lightweight hybrid torpedo
LIDAR	Light detection and ranging
LLNL	Lawrence Livermore National Laboratory
LMRS	Long-range Mine Reconnaissance System
LO	Low observable
LOS	Line of sight
LOVA	Low-vulnerability ammunition
LOX/LH_2	Liquid oxygen/liquid hydrogen
LP	Liquid propellant
LPD	Amphibious transport dock

LSD	Landing ship dock
MAD	Mutual assured destruction
MaRV	Maneuverable reentry vehicle
MCM	Mine countermeasures
MEADS	Medium extended air defense system
MEF	Marine Expeditionary Force
MEMS	Microelectromechanical System
MEU	Marine expeditionary unit
M_f	Mass fraction
MHIP	Missile Homing Improvement Program
MIRV	Multiple independently targetable reentry vehicle
MLRS	Multiple-launch rocket system
MMIC	Millimeter microwave integrated circuit
MMW	Millimeter wave
MOD	Minstry of Defense (Israel)
MPF	Maritime prepositioned force
MRC	Major regional conflict
MTI	Moving-target indicator
NACO	Navy cool (propellant)
NASA	National Aeronautics and Space Administration
NAWC	Naval Air Warfare Center
NMD	National Missile Defense
NSF	National Science Foundation
NSFS	Naval surface fire support
NSWC/IHD	Naval Surface Warfare Center, Indian Head Division
NTM	National Technical Means
NTO	3-Nitro-1,2,4-triazol-5-one
NUWC	Naval Undersea Warfare Center
NUWC/K	Naval Undersea Warfare Center, Keyport
OMFTS	Operational Maneuver From the Sea
ONR	Office of Naval Research
OOTW	Operations other than war
OSD	Office of the Secretary of Defense
OTCIXS	Officer Tactical Command Information Exchange System
OTH	Over-the-horizon
P^3I	Preplanned product improvement
PBD	Polybuta-diene
PBX	Plastic-bonded explosive
PGB	Precision-guided bomb
PGM	Precision-guided missile
PIM	Pulse intermodulation (codes)
P_k	Probability of kill
P_k^{ss}	Single-shot probability of kill

PMM	Programmable mobile machine
POM	Program Objectives Memorandum
PRF	Pulse-repetition frequency
PSTN	Public switched telephone network
PSYOPS	Psychological operations
R&D	Research and development
RAM	Radar absorbant material; also, rolling airframe missile
RAP	Rocket-assisted projectile
R(B)DS	Radio (Broadcast) Data System
RCS	Radar cross section
RDX	Cyclotrimethylenetrinitramine
RECCE	Reconnaissance
RF	Radio frequency
RL	Receive location
RLG	Ring-laser-gyro
ROE	Rule of engagement
RSTA	Reconnaissance, surveillance, and target acquisition
RV	Reentry vehicle
S&T	Science and technology
SA	Surface-to-air
SABRE	Shallow-water assault breaching system
SADARM	Search-and-destroy armor munition
SALT	Strategic Arms Limitations Treaty
SAM	Surface-to-air missile
SAR	Synthetic aperture radar
SATCOM	Satellite communications
SBIRS	Space-based infrared system
SBL	Space-based laser
SCEPS	Stored chemical energy propulsion system
SDI	Strategic Defense Initiative
SEAD	Suppression of enemy air defenses
SEAL	Sea, air, land (team)
SFW	Sensor-fused weapon
SHS	Self-propagating high-temperature synthesis system
SIGINT	Signal intelligence
SLAM-ER	Submarine-launched land attack missile—extended range
SLBM	Submarine-launched ballistic missile
SLCM	Submarine-launched cruise missile
SLID	Small low-cost interceptor device
SLMM	Submarine-launched mobile mine
SM	Standard missile
SMAW	Shoulder-launched multipurpose assault weapon
SOF	Special operations forces

SOW	Standoff weapon
SRAW	Short-range antiarmor weapon
SSBN	Nuclear-powered ballistic missile submarine
SSDC	Space and Strategic Defense Command
SSGN	Nuclear-powered guided-missile submarine
SSN	Nuclear-powered submarine
START	Strategic Arms Reduction Treaty
TACAIR	Tactical aircraft
TACAWS	The Army Combined Arms Weapon System
TADIX	Tactical Data Information Exchange
TAZDN	Triazido carbonium dinitramide
TBM	Theater ballistic missile
TBMD	Theater ballistic missile defense
TEL	Transportable erector launcher
THAAD	Theater high-altitude air defense
THEL	Tactical high-energy laser
TIBS	Tactical Information Broadcast System
TLAM	Tomahawk land attack missile
TLE	Target location error
TM	Tactical missile
TMD	Theater missile defense
TOW	Tube-launched optically wire-guided
TPE	Thermoplastic elastomer
TPU	Torpedo propulsion upgrade
TRAP	Tactical receive and related applications
TRE	Tactical receive equipment
TRM	Technology requirements model
TSSAM	Tri-Service standoff attack missile
TVC	Thrust vector control
UAV	Unmanned aerial vehicle
UUV	Unmanned underwater vehicle
UV	Ultraviolet
UWB	Ultra-wideband
UWB RF	Ultra-wideband radio frequency (impulse)
UWEF	Undersea Weapons Evaluation Facility
VGAS	Vertical gun system
VHF	Very high frequency
VLS	Vertical launch system
VTOL	Vertical takeoff and landing
WAF	Weapons Analysis Facility
WAGE	Wide-area GPS enhancement
WMD	Weapons of mass destruction
WSMR	White Sands Missile Range